VIGYAN 2047

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HISTORY OF LIGHT | SAMUEL HAHNEMANN
TRIBOLOGY | STEM IN CENTRAL ASIA
THE WILD MATHEMATICS OF MODERN WAR

Stars, Sugar, Science

Three Journeys that changed India

VIGYAN 2047

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STEM the Turbulence

The world today stands at a restless crossroads. From Eastern Europe to West Asia, from tensions in our neighbourhood to sporadic conflicts across continents, geopolitics appears increasingly shaped by confrontation. Nations continue to invest heavily in military strength. In 2024 alone, global military expenditure reached about $2.7 trillion—the highest level ever recorded, marking the tenth consecutive year of rising defence spending.

Yet beneath this shadow of conflict lies another force quietly shaping humanity's future—science and technology. Science has always been intertwined with history. The same ingenuity that produces advanced weaponry also builds satellites that guide navigation, monitor the Earth's climate, and help farmers manage crops with remarkable precision. It powers artificial intelligence, delivers life-saving vaccines, and drives new energy systems. Science therefore embodies a profound paradox: it can intensify conflict, yet it also holds the power to foster cooperation and shared progress.

Today, the greatest challenges confronting humanity cannot be solved through military strength alone. Climate change, pandemics, food insecurity, water stress, and the global energy transition are fundamentally scientific challenges that demand international collaboration.

Consider food security. Despite extraordinary advances in science and technology, about 673 million people still suffer from hunger, while nearly 2.3 billion people experience moderate or severe food insecurity worldwide. Conflict remains one of the most powerful drivers of hunger, pushing millions into food crises across fragile regions. In such circumstances, agriculture becomes far more than an economic activity—it becomes a pillar of global stability. Advances in agricultural science—drought-resistant crops, satellite-based crop monitoring, climate-smart irrigation, and data-driven farming—are enabling nations to secure food supplies even amid geopolitical uncertainty. In many ways, the quiet labour of farmers, supported by modern science, contributes as much to peace as the work of diplomats and policymakers.

For younger generations, this message carries profound importance. Scientific literacy today is not merely about mastering equations or laboratory techniques. It is about understanding how technological systems influence governance, economies, diplomacy, and everyday life.

Artificial intelligence is transforming decision-making. Satellites observe the health of our planet. Biotechnology is reshaping medicine and agriculture. Digital networks connect billions of people and ideas. In such a world, the ability to understand science becomes an essential component of responsible citizenship.

Science can help nations defend themselves—but it can also help them understand one another. It can build systems of security while simultaneously creating networks of cooperation across borders. It can develop technologies of power, yet also nurture technologies of healing, sustainability, and shared prosperity.

Ultimately, the destiny of science does not lie in laboratories alone. It lies in the choices humanity makes.

If guided by wisdom and creativity, the spirit of STEM—linking knowledge, innovation and human values—can help humanity move beyond cycles of conflict toward a more resilient and cooperative world.

For in the long journey of civilization, the most enduring victories will not be those won on battlefields, but those achieved through knowledge, soil, satellites, and the shared pursuit of discovery.

Nakul Parashar, PhD
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YOUR LETTERS

Excellent Issue

I recently had the pleasure of reading the March 2026 issue of Vigyan 2047, and I must say it stands out as one of the finest collections of science writing I have encountered in recent years. The thoughtful selection of articles blends historical insight, contemporary challenges, and forward-looking analysis in a way that both educates and inspires. The cover story on Grace Hopper captures her pioneering spirit with remarkable clarity, highlighting her role in creating machine-independent programming languages like FLOW-MATIC and her influence on COBOL—innovations that continue to shape computing today. Equally compelling is the piece on women in Indian science policy, which lays bare the structural barriers to retention and progression while offering practical policy recommendations, such as treating childcare as research infrastructure. Articles on Linda Buck's olfactory receptor discoveries and the rich Asian history of optics, from Aryabhata's eclipse theories to Ibn al-Haytham's experimental methods, further enrich the issue, reminding us of light's enduring role across civilizations. Even the more applied pieces, like the examination of tribology's energy-saving potential in India's road transport sector and the nuanced discussion of homeopathy in neurological disorders, demonstrate the magazine's commitment to relevance and balance. In an era when science communication often prioritizes sensation over substance, Vigyan 2047 excels by making complex ideas accessible without sacrificing depth. Thank you for producing such a high-quality publication. I look forward to future issues and encourage you to keep championing these vital conversations.

Swagata Chatterjee
E: swagata.nandy@gmail.com

Thank you, Ms Chatterjee for your kind words.—Editor

Critical Observations

Thank you for bringing out Vigyan 2047. However, have we thought Vigyan (Science) ... who is it for? In my opinion the magazine sits between popular science and academic writing, and hence, definitely not for young readers or students.

Reasons why it does not suit the young

- Long, dense paragraphs with little visual explanation.
- Language is analytical and policy-oriented rather than storytelling.
- Very few illustrations, diagrams, or engaging graphics.
- Articles are essay-style rather than short, fast-paced science pieces.
- Topics often discussed at conceptual or policy level rather than through simple examples. It is also not a research journal either – lacks technical depth and formal referencing expected by academics.

Topics suit—scientists, research scholars, faculty, and policy thinkers.

Strong science—policy orientation—emphasis on science, technology, innovation, and India@... Overall: it reads more like a policy-oriented science magazine ONLY for Science minded adults, not a youth science interest generating magazine.

Abhijit Dasgupta
E: sukrititv@gmail.com

Thank you, Mr Dasgupta for your observations and hence, suggestions. We agree with most of them and would start incorporating them at the earliest.—Editor

Valuable Advise

Yes, after a significant break I am writing you this long overdue email.

I was thinking about sharing some thoughts related to both Vigyan 2047 as well as Bangla Bigyan Katha. These are not very lofty ideas though frankly speaking, as I to a certain extent understand the constraints under which the publications are brought out.

I can identify the suitable topics but not always the suitable authors. It appears for Bigyan Katha article wise we are having a tightrope walk. Can we make a long time plan and provide the identified authors longer time with reminders in between? A challenging task indeed. And it is even more difficult for an English publication. Interestingly we are having so many students coming out of Colleges and Universities with entirely English medium background during their student lives, yet it is difficult to find interested younger people for writing.

Since we talk about short attention spans, can we try out a section, may be, one or at best two pages where we can try to put some short interesting stuff with catchy headlines.

Contributors for the English publication are difficult to identify. I do have a plan to convert some of my selected popular science publications in other magazines to English. Please give your valuable opinion in this regard. Please suggest if that would be an acceptable step.

These are some of the thoughts that I wanted to share with you. I fully understand the position of print materials in popular science and I often find how the old ones are changing themselves to cope up with the prevailing scenario. Yet it is not always giving fruits.

I wholeheartedly appreciate your untiring efforts in bringing science to the general public.

Bhupati Chakravorty
chakrabhu@gmail.com

Thank you, Prof Chakravorty for your observations and hence, suggestions. We are keen to accomplish more through these points of observation. Your support to the magazine is highly appreciated. __Editor

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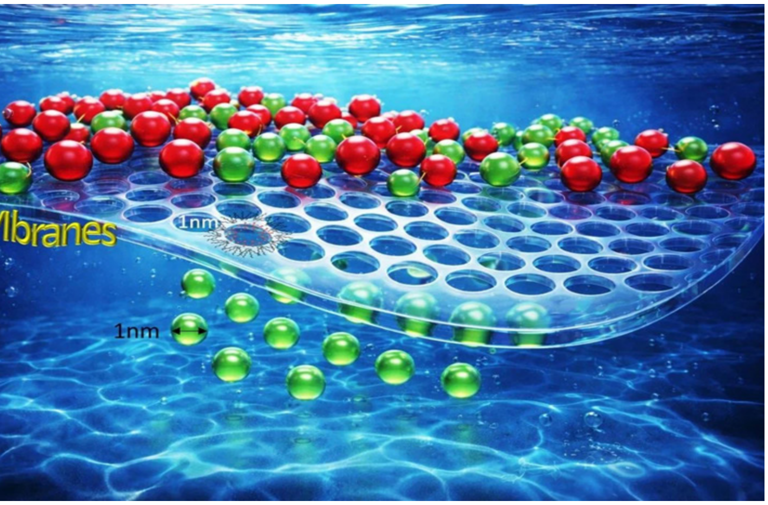
News this month

More effective ultra-thinner molecular filter



Scientists from CSIR–Central Salt and Marine Chemicals Research Institute, Indian Institute of Technology Gandhinagar, Nanyang Technological University, and S. N. Bose National Centre for Basic Sciences have developed an ultra-precise filtration membrane that can sort molecules with exceptional accuracy. The work, published in the *Journal of the American Chemical Society,* introduces "POMbranes," crystalline membranes built from polyoxometalate clusters. Unlike conventional polymer membranes, whose pores vary in size and degrade over time, POMbranes contain fixed, one-nanometer-wide channels. These permanent pores ensure stable and reliable separation, even under harsh industrial conditions. Inspired by biological water channels called aquaporins, the membranes allow only molecules of specific size and shape to pass through. By attaching flexible chains to the clusters, researchers enabled the material to self-assemble into large, continuous films suitable for scalable manufacturing. Tests showed that the membranes can distinguish molecules differing by just 100–200 Daltons, far exceeding the precision of existing technologies. This breakthrough could significantly reduce energy use in purification processes and support sustainable manufacturing. It holds particular promise for India's textile and pharmaceutical industries, where efficient wastewater treatment, solvent recovery, and drug purification are critical. Overall, POMbranes represent a major step toward cleaner, low-carbon industrial separations.

◆

Southern Indian Ocean is losing salt

A new study published in *Nature Climate Change* reveals that the Southern Indian Ocean off Western Australia is becoming rapidly less salty, a process known as freshening. Researchers from University of Colorado Boulder found that rising global temperatures over the past 60 years have altered wind patterns and ocean currents, redirecting large volumes of freshwater into the region. According to lead scientist Weiqing Han, this shift is occurring in an area crucial to global ocean circulation. Much of the freshwater originates from the Indo-Pacific freshwater pool, a rain-rich tropical zone, and is carried southward by changing currents. The study shows that salty surface waters in the region have declined by nearly 30 percent, the fastest freshening in the Southern Hemisphere. First author Gengxin Chen estimates that the added freshwater is equivalent to about 60 percent of Lake Tahoe each year. Lower salinity reduces seawater density, strengthening surface layering and weakening vertical mixing. This can disrupt nutrient circulation, warm surface waters, and threaten marine ecosystems. The changes may also affect the global "conveyor belt" circulation, already stressed by freshwater from the Greenland Ice Sheet. Scientists warn that continued freshening could have serious consequences for climate stability and ocean life worldwide.

◆

AI reveals new physics in plasma

Researchers at Emory University have used artificial intelligence to uncover new physical laws governing dusty plasmas, a type of ionized gas containing charged particles. Their study, published in *Proceedings of the National Academy of Sciences,* combines laboratory experiments with a specially designed neural network to analyze complex particle interactions. Led by physicist Justin Burton and theorist Ilya Nemenman, the team showed that AI can do more than analyze data—it can help discover previously unknown physics. Their model accurately described non-reciprocal forces, in which particles influence each other unevenly, with over 99% precision. First author Wentao Yu developed advanced 3D imaging to track particle motion, while Eslam Abdelaleem contributed to the analysis. The researchers found that some long-standing theories about particle charge and force decay were incomplete and needed correction. Funded mainly by the National Science Foundation, the project shows how carefully designed AI systems can reveal hidden rules in complex systems. The approach may be applied to materials, fluids, and even living cells, offering a powerful new tool for scientific discovery. ◆

Is writing 40,000 years old?

A new study by linguist Christian Bentz of Saarland University and archaeologist Ewa Dutkiewicz from the Museum für Vor- und Frühgeschichte suggests that early humans were encoding information tens of thousands of years before formal writing appeared. The researchers analyzed more than 3,000 engraved signs carved on 260 Paleolithic objects dating from 34,000 to 45,000 years ago. Many of these artifacts were found in the Swabian Jura, including discoveries from Vogelherd Cave, Geißenklösterle Cave, and Hohlenstein-Stadel Cave. These objects feature repeated patterns of lines, dots, notches, and crosses, carefully arranged on tools and figurines. Using computational linguistics and statistical modeling, the team studied how often signs appeared and how predictable their sequences were. They found that these markings show levels of complexity and information density similar to proto-cuneiform, one of the earliest known writing systems. The findings, published in PNAS, were unexpected. Although the symbols do not represent spoken language, the researchers argue they were intentional and meaningful. They may have helped early humans record, organize, and transmit knowledge. The study suggests that symbolic communication evolved gradually over tens of thousands of years, forming an important foundation for later writing systems and modern information technologies. ◆

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COVER STORY

Stars, Sugar, and Science: Three Journeys That Changed India

TV Venkateswaran

Morning you wake up with a longing for coffee (or tea or milk). When you sit down for your filter coffee, let us assume, and you put in that first spoon of sugar, do you ever wonder where that sugar comes from? Not the shop. Not the brand. Deeper. The sweetness itself. The fact that you can buy sugar grown on Indian soil, refined in Indian mills is largely due to an extraordinary woman from a marginalised community. This woman is behind that sweetness.

But I am getting ahead of myself.

The Patent Clerk Who Unmade the Universe

First, think of a man sitting in a patent office in Bern, Switzerland, 1905. He is 'third class', that is the official designation. He is 'patent clerk third class'. His job is to look at other people's inventions, decide if they are original, file the paperwork. Push papers, warm the desk. Not the kind of work that makes history. Except he is making history while doing it. Between reviewing applications for machines no one remembers, he pulls out sheets of paper and writes. Thoughts that come into his mind.

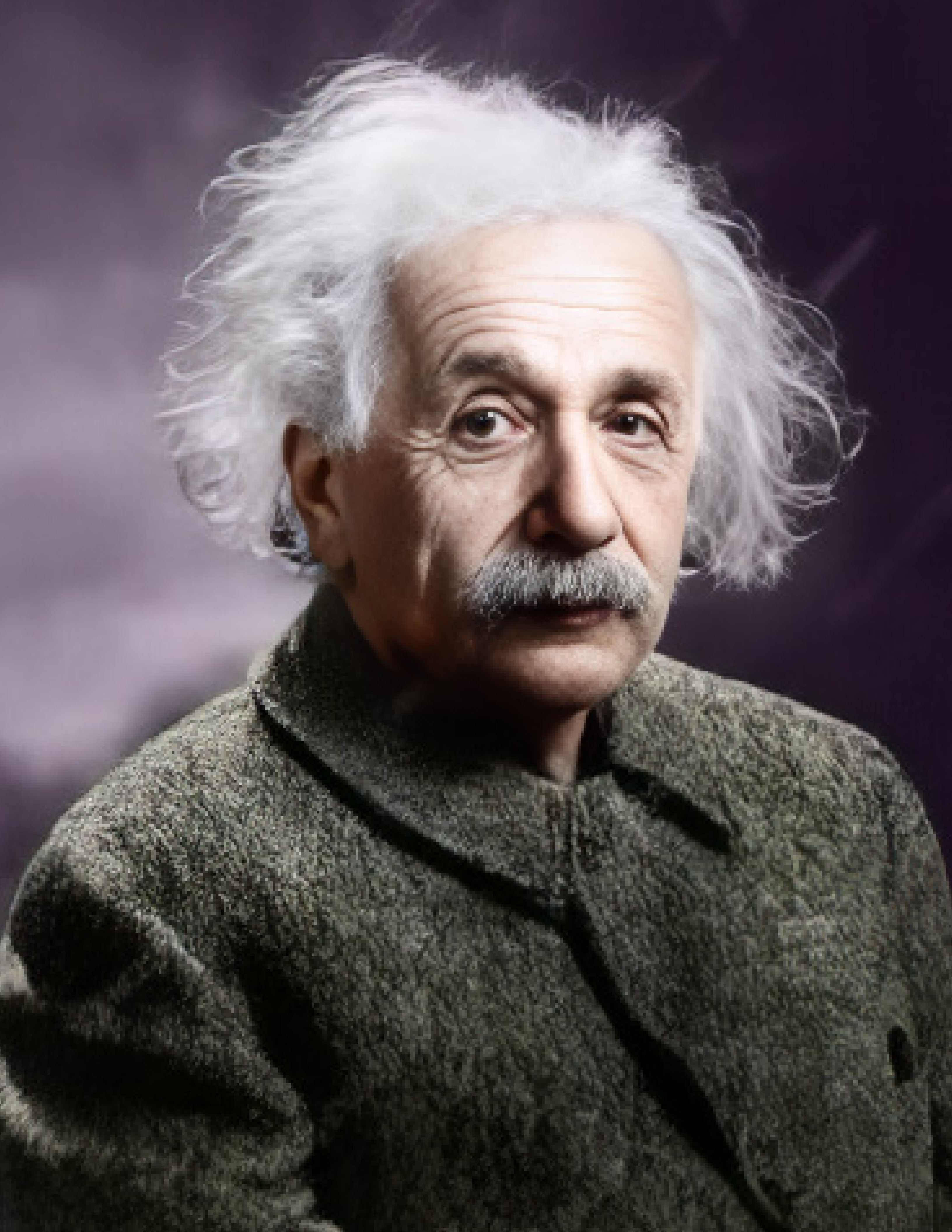
Four papers, in one year, for a journal called Annalen der Physik; the top level scientific journal of those days. One paper on light, suggesting that it comes in packets, quanta. This paper became the foundation for the evolution of quantum mechanics. One paper on particles suspended in liquid, proving mathematically that atoms actually exist. Not a theory, not a speculation, but a thing you can calculate. One paper on electrodynamics, saying that the speed of light is constant, irrespective of the motion of the source. This paper develops into the theory of relativity. And then one more, barely a page, that gives the world an equation you have seen on t-shirts and posters: e equals m c squared.

I am sure you have guessed; yes indeed it is Einstein. But here is what the posters do not show. Before all this, he could not get a teaching job. His doctoral thesis, and this might surprise you, was not on relativity. It was called "A New Determination of Molecular Dimensions." A quiet lustreless title. When a French physicist named Jean Perrin later did experiments that confirmed Einstein's calculations, Perrin got the Nobel Prize for proving atoms exist. Einstein's work made it possible. Ironically Nobel committee, when they finally gave him the prize in 1921, did not mention relativity. They gave it for the photoelectric effect. Relativity was too controversial, they said. They wanted to honour the man without endorsing the theory.

Einstein demolished classical physics, but the alternative that he built was so vast that even he spent the rest of his life trying to understand it.

In 1909, the University of Zurich was looking for a professor. Two candidates were shortlisted. One was Einstein. The other was a man named Friedrich Adler. Many of us may not have heard the name of Adler at all. But the selection committee preferred Adler. He had better academic records, good scores and all that. However, Adler himself stepped aside. He said, give the job to Einstein. He is the best of both of us. Later Adler left physics and became a revolutionary, fighting for justice and socialism. Years later, when Adler was on trial for assassinating the Austrian Prime Minister, a political act against the imperialist war, Einstein wrote a letter in his support.

> **In 1909, the University of Zurich was looking for a professor. Two candidates were shortlisted. One was Einstein. The other was a man named Friedrich Adler. Many of us may not have heard the name of Adler at all. But the selection committee preferred Adler. He had better academic records, good scores and all that.**



Let me tell you another story about Einstein. After he got Nobel, he became very famous. He used to travel to universities to give lectures. His driver, a man who had heard the same lecture thirty times, said one day: Dr Einstein, I could give that lecture myself. Einstein smiled and said: all right, let us try. People don't know me at the next venue, you sit in the back, put on my coat and act as if you are Einstein, I will sit in your place with your driver's cap and act as if I am the driver; let us see what happens.

At the next university, the driver put on Einstein's coat, introduced himself as Dr Einstein, and delivered the lecture perfectly. Just to see what occurs in the hall, Einstein in the guise of driver stood at the back of the hall. The audience were impressed by the lecture. There was pin drop silence all through the talk. At the end spontaneously the auditorium erupted in claps. The driver in the guise of Einstein was brimming with smile; and Einstein pretending to be the driver was amused.

Just then, a professor in the audience stood up; he asked a complex question, full of equations. For a minute the driver was taken aback; but then gave a sly smile. He said: the answer is so simple, I am surprised you had to ask. You don't need me to answer this question. I will let my driver come up and answer it. And of course the person in the guise of the driver was Einstein.

The story is most likely not true. But the legend endures because it contains a vital truth about the nature of science. Science is not about who says what. It is about whether anyone can verify them. Do you have evidence to support your claim? Can it be verified? How far does the evidence support the inferences? It is open and public knowledge. Belongs to whoever can understand it. If you make effort you can become Einstein. It does not matter if you are western or eastern, black, brown or white; male or female. Science is for everyone; it is human heritage.

Streetlight to stars

Now let us cross from Bern to Calcutta. A boy named Meghnath is born on a stormy night. His parents call him Meghnath, Lord of the Clouds, because of the thunder and rain. Later, he will change his name to Meghnad, after the tragic hero of Michael Madhusudan Dutt's epic Meghnad Badh Kabya. Meghnad, also known as Indrajit ("Conqueror of Indra"), is a prominent, invincible warrior in the Ramayana epic, recognised as the eldest son of

Ravana, the demon king of Lanka. Known for his exceptional skills, he defeated Indra, king of gods, and twice defeated Lakshmana using magical abilities and celestial weapons like the Brahmastra. He was killed by Lakshmana while performing a yajna to Goddess Nikumvila, aided by the betrayal of his uncle, Vibhishana.

Why change his name? Because there was something in that story of defiance that resonated with him. Born to a poor shopkeeper and from a marginalised community, he had to face hardship. Studied under streetlights because there was no other light. Rowed a boat through floodwaters to reach his school. A few upper caste students discriminated against him in school and college.

This is Meghnad Saha. As a student, he was expelled from Dhaka College for protesting British colonial tyranny. In college, he faced discrimination from students of dominant castes who did not want him in the dining hall. When he was proposed for the Royal Society in 1925, the Viceroy's office had him investigated. The special agents thought he was a revolutionary, a conduit for Indian radicals in Germany and Switzerland. It took two years for the election to go through, and only because other scientists insisted that his politics should not stand in the way of recognising his work.

What work? The Saha equation. Every astronomy student learns a mnemonic: "Oh Be a Fine Girl/Guy, Kiss Me Right Now." A way to remember the sequence of stellar spectra. If one classifies all the stars, we find some are hottest and some relatively cool. O class stars are the hottest and N class stars are the coolest. OBAFGKMRN is the order of stars according to their surface temperature.

Annie Jump Cannon and Henry Norris Russell had figured out the order. They did not know why this order. Saha explained why the order is in that way. He showed that the differences in spectral lines were not because stars were made of different elements. They were because of temperature. At very high temperatures,

"Oh Be a Fine Girl/Guy, Kiss Me Right Now." A way to remember the sequence of stellar spectra. If one classifies all the stars, we find some are hottest and some relatively cool. O class stars are the hottest and N class stars are the coolest. OBAFGKMRN is the order of stars according to their surface temperature.

hydrogen becomes ionised, its electrons stripped away, so its spectral lines disappear or become very dim. That is why O stars, the hottest, do not show strong hydrogen lines. It is not because hydrogen is missing from these stars. It is because the star is too hot for hydrogen to keep its electrons in its lower orbit. Cecilia Payne-Gaposchkin would use Saha's equations in her doctoral thesis to prove that stars are mostly hydrogen — a discovery that transformed astronomy.

The boy who studied under streetlights grew into a man who read Einstein in German original, who translated for the first time the papers on relativity from German into English with Satyendra Nath Bose, who saw early that uranium fission was the future and began building India's nuclear programme. Nominated for the Nobel Prize seven times. Never got it. There is something about his story that echoes the Meghnad of the epic; the one who defeated Indra but was himself slain, remembered but not celebrated. But Indian science will not be what it is today, if not for his contribution. He and his students were key in the establishment of a number of scientific fields in India.

The princess of Ellis island

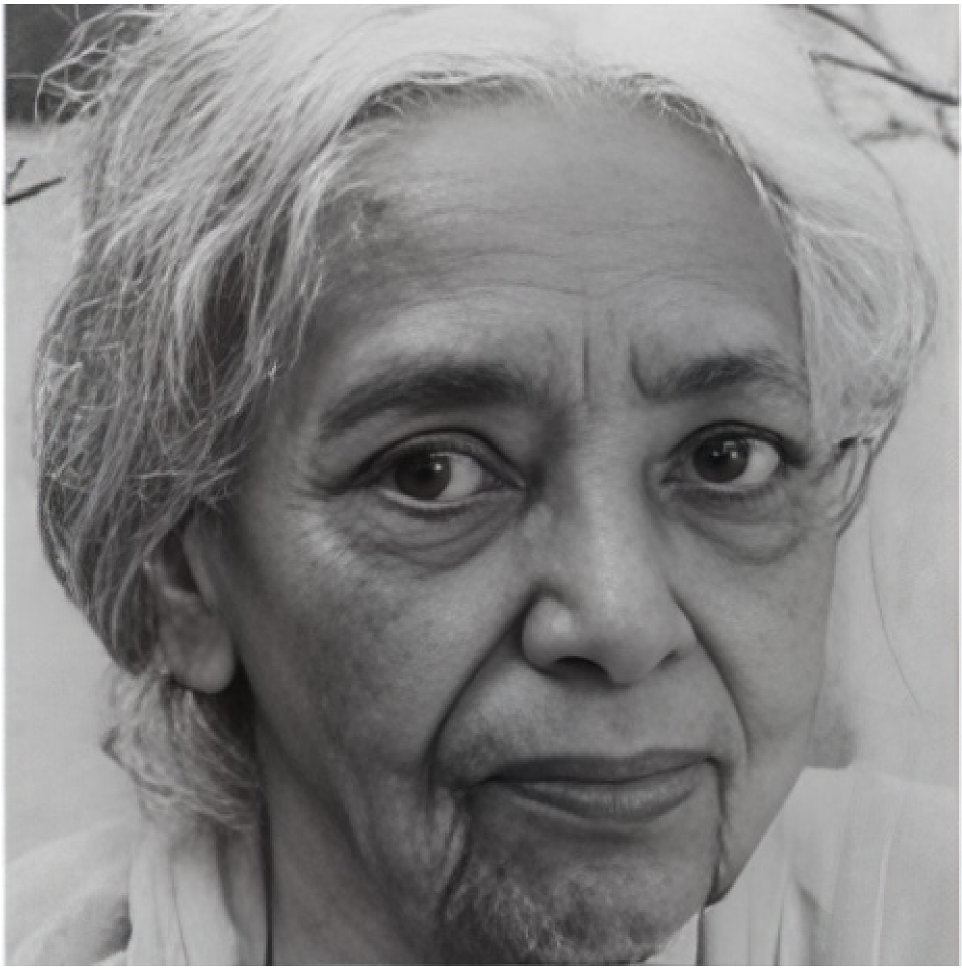
Now let me come to the woman I mentioned at the beginning. The one with the sugar. 1924. A ship arrives in New York. The 'foreigners' are segregated and placed in the Ellis Island immigration station. A young Indian woman is also shown the way to the barracks to be sent back. The Immigration Act of 1924 has just been passed. It creates an "Asiatic Barred Zone", people from India are not supposed to enter the USA.

She is dark-skinned, Asian, wearing a silk saree, her hair long and black. She was standing tall full of confidence. An immigration officer looks at her. He sees the saree, the bearing. He thinks she must be an Indian princess; perhaps his immigration officials had made a mistake. He approaches her and asks: are you an Indian princess? She does not say no. She nods. They let her through.

Her name is Janaki Ammal. Born in 1897 in Thalassery, Kerala, the tenth of nineteen children. Her family was considered untouchable, avarna, outside the caste order. Her father was a judge in a subordinate court, but he had a passion for science, for life sciences, for the birds of North Malabar. He wrote two books about them. Janaki caught that passion early.

Her sisters were married, as was the custom, at a young age. She said no. She would study. In 1913, literacy among Indian women was less than one per cent. Fewer than a thousand women in the entire country were enrolled in school above tenth grade. She went to Queen Mary's College in Madras, and later to Presidency College. She taught for three years at the Women's Christian College. Then she got a scholarship, the Barbour Scholarship, established at the University of Michigan for Asian women. They called it the "oriental girls scholarship." She went alone to the USA in 1924.

At Michigan, she studied plant cytology. The genetic composition of plants. The patterns of gene expression. She specialised in making hybrids, crossing different species to get better traits: disease resistance, faster growth, higher yield. Like mules, the offspring of horses and donkeys, but with plants. She got her Master's in one year. In 1931, she got her doctorate.



She came back to India, taught at Maharaja's College in Trivandrum. Then in 1934, she joined the Sugarcane Breeding Institute in Coimbatore. At that time, the sweetest sugarcane came from Papua New Guinea: Saccharum officinarum. Also India was importing sugar. The sugarcane grown in India did not give enough yield, nor had good sugar content. Madan Mohan Malaviya and other nationalists had argued years before that India should develop its own varieties; should undertake agricultural innovation. The Institute was created for that purpose. Janaki Ammal crossed native sugarcane with Saccharum officinarum. She crossed sugarcane with maize, with millet, with bamboo, things no one had tried. The results were the "Co-canés"—Coimbatore canes. Sweeter than the native varieties. Adapted to Indian conditions. Giving copious yield with a lot more sugar content.

But let me tell you about the conditions she worked in. At the Institute, she faced male prejudice. Caste prejudice. Moreover she was single; unmarried. That led to a lot of sexual harassment. In 1938, a biologist named Reginald Ruggles Gates visited the institute. His ideas were not aligned with Janaki's research. He doubted the results Janaki's experiments had produced. The head of the Institute was so impressed by Gates that he stalled Janaki's paper to Nature for months. She fought. The paper was submitted. Nature published it. And today it is one of the celebrated works in plant cytology. The ambience at the institute was so bad that she could not stay on.

In 1940, she went to London. To the John Innes Horticultural Institute. There she worked with Cyril Dean Darlington on the Chromosome Atlas of Cultivated Plants, listing the chromosome numbers of a hundred thousand plant species. The publication of this atlas shook the world. It is still a standard reference. She is world known for this great work. Then the Blitz came. Nazis were raining bombs on London during the Second World War. She hid under her bed at night and worked in her labs in the mornings, as if nothing had happened.

In 1946, the Royal Horticultural Society offered her a paid position. She was the first woman to work there.

When India became free, Jawaharlal Nehru requested her to come back. To head the Central Botanical Laboratory in Lucknow. To reorganise the Botanical Survey of India, which had been run from

Kew Gardens in Britain, its specimens collected by foreign botanists, studied in foreign herbaria. Indians had a role in helping the collection of native species. Janaki Ammal insisted: how can we know our own flora if everything is on foreign soil? She argued for Indian collection, Indian study. For valuing indigenous knowledge. She radically changed the way the institution functioned; she changed it from a colonial institution into a national institute.

In 1955, she was the only woman at an international symposium in Chicago. The title was Man's Role in Changing the Face of the Earth. She was changing the face of Indian agriculture, quietly.

Janaki Ammal bloomed in conditions that would have crushed most people. Shunned by others as untouchable. A woman in a field of men. A scientist in a colonial system. An Indian in a country that had closed its doors to Asians. Yet she stood tall.

Every spoon of sugar you put in your coffee carries her invisible hand. India is now the world's second-largest producer of sugar, the largest consumer, the second-largest exporter. This is because she made it possible for India to grow its own, to stop importing sweetness, to build something that would last.

They helped India stand on its Legs

Of the three people we saw two were Indians; but you may wonder why Einstein, a westerner, is part of this list. What is the connection?

Albert Einstein was an honorary president and a prominent supporter of the international movement, The League Against Imperialism and Colonial Oppression. This organisation was officially founded in Brussels in 1927 and argued for national liberation. Jawaharlal Nehru was also part of this association; both Einstein and Nehru argued that each country, including India and countries in Africa and Asia, must be free, independent from imperialism. Thus, Einstein was not just a famous scientist, he directly supported the cause of India's independence from British colonial rule.

> **... both Einstein and Nehru argued that each country, including India and countries in Africa and Asia, must be free, independent from imperialism. Thus, Einstein was not just a famous scientist, he directly supported the cause of India's independence from British colonial rule.**

Three lives. Einstein, who sat in a patent office and reshaped the universe. Saha, who studied under streetlights and explained the stars. Janaki Ammal, who nodded when they mistook her for a princess and spent her life making the land more abundant. We owe a lot to people like them for what we are today.

They were pioneer planters. They did not wait for the field to be ready. They worked with what they had. Floodwaters. Discrimination. War. A patent clerk's desk.

And the field continues to yield. ◆

__Prof. T. V. Venkateswaran__ is currently a Professor at IISER Mohali. A prolific science writer and distinguished science communicator, he brings over four decades of rich experience to the field. This article is based on his National Science Day lecture delivered at the Satish Dhawan Space Centre (SDSC SHAR), Sriharikota, on March 4, 2026. He can be contacted at tvv123@gmail.com.

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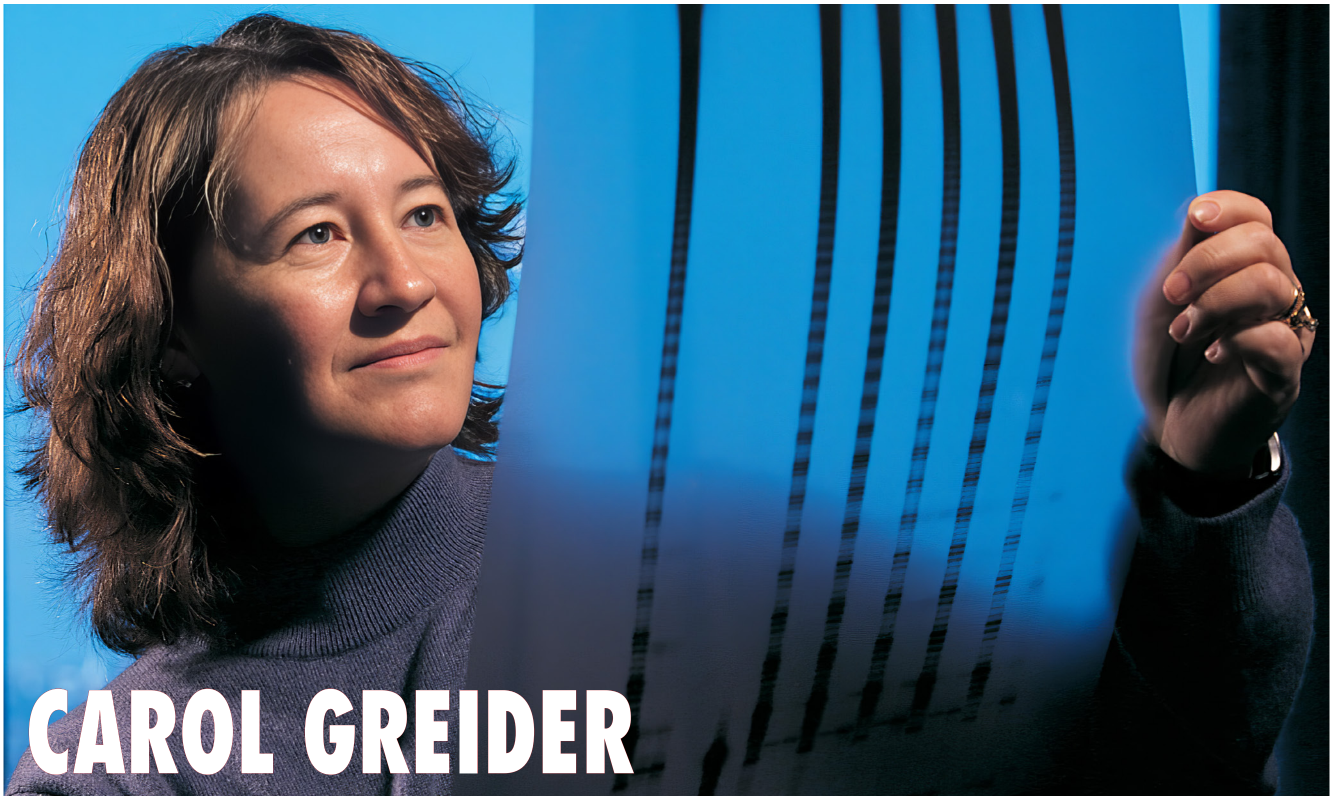
WOMEN NOBEL WINNERS IN SCIENCE



JONES HOPKINS MEDICINE

CAROL GREIDER

TELOMERASE, PERSISTENCE, AND THE SECRETS OF CELLULAR AGEING

Editorial Note: In an earlier article in this series, Vigyan 2047 featured Elizabeth Blackburn, whose pioneering research laid the foundations for understanding telomeres. In this issue we present the work and life of Carol W. Greider, Blackburn's collaborator and co-recipient of the 2009 Nobel Prize in Physiology or Medicine, who together with Blackburn and Jack W. Szostak revealed how chromosomes are protected by the enzyme telomerase.

Scientific discovery rarely follows a smooth or predictable path. It is shaped by curiosity, persistence, and the courage to question what others take for granted. Few scientific journeys illustrate this better than that of Carolyn Widney Greider, the American molecular biologist whose research uncovered one of the most fundamental mechanisms of life: how chromosomes protect themselves during cell division.

Her discovery of telomerase, an enzyme that maintains the ends of chromosomes, transformed our understanding of cellular ageing, genetic stability, and cancer biology. Today Greider is recognised as one of the pioneers of telomere biology, a field that explores how cells maintain their genetic integrity over time. She currently serves as Distinguished Professor of Molecular, Cell, and Developmental Biology at the University of California, Santa Cruz, where her laboratory continues to investigate the biological consequences of telomere dysfunction.

Carol Greider was born on April 15, 1961, in San Diego, California, into an academic family. Her father, Kenneth Greider, was a professor of physics. The family later moved to Davis, California, where she spent much of her childhood and eventually graduated from Davis Senior High School in 1979.

Despite growing up in a scholarly environment, Greider faced serious challenges in school. As a child she struggled with dyslexia, which made reading and spelling difficult. She often reversed letters or words and found it difficult to follow conventional reading methods. Because of these difficulties she was placed in remedial classes, an experience that left her feeling academically inadequate.

Yet these struggles also pushed her to develop new strategies for learning. Instead of sounding out words, she began memorising words and their spelling patterns. This method helped her overcome reading difficulties and sharpened her ability to recognise patterns—a skill that later proved invaluable in scientific research.

Greider has often remarked that dyslexia may have shaped her thinking in unexpected ways. Scientists frequently need to hold multiple possibilities in mind and interpret complex patterns in data. Her compensatory learning strategies encouraged exactly this kind of thinking.

Her childhood also involved personal loss. When she was six years old, her mother died. The experience forced Greider and her brother to grow up with a strong sense of independence. Later, when her father spent a year in Heidelberg, Germany, on a research sabbatical, Greider attended school there and learned to adapt to new environments.

During her teenage years Greider gradually realised that subjects such as biology and history suited her strengths. Her ability to memorise and analyse patterns helped her excel in these areas.

After finishing high school she joined the College of Creative Studies at the University of California, Santa Barbara, where she earned a Bachelor's degree in Biology in 1983. Initially she planned to specialise in marine ecology, but her interests shifted after she began working in a laboratory.

A major influence during this period was Beatrice Sweeney, a professor who encouraged Greider to pursue laboratory research. Under Sweeney's guidance Greider discovered that scientific work was not simply about memorising facts—it involved asking questions, designing experiments, and interpreting surprising results. During her undergraduate years she also spent time studying at the University of Göttingen in Germany, gaining valuable exposure to international research.

When Greider applied for graduate studies in molecular biology, she once again encountered obstacles. Her GRE scores were relatively low, partly due to dyslexia, and many universities rejected her application. She applied to several programmes and was accepted by only two institutions: the California Institute of Technology (Caltech) and the University of California, Berkeley. Greider ultimately chose UC Berkeley, a decision that would lead to one of the most important discoveries in modern biology.

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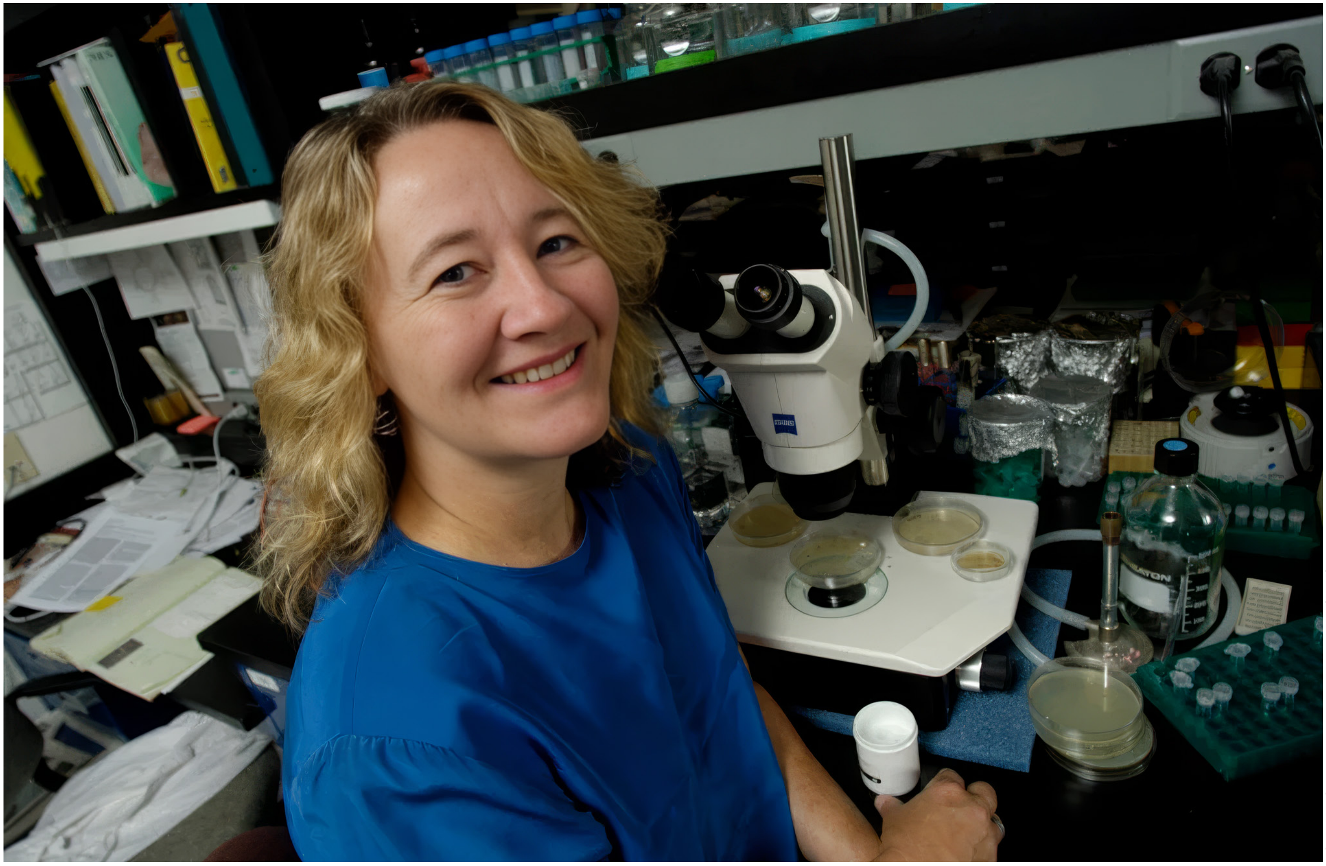
Carol Greider in her laboratory at Johns Hopkins University, 2009.



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Telomeres: Protectors of the Genome

Chromosomes carry the DNA that stores genetic information. At their ends lie specialised DNA sequences called telomeres, which act as protective caps, preventing chromosomes from fraying or fusing during cell division. Scientists had observed that telomeres gradually shorten each time a cell divides, raising an important question: if this process continued indefinitely, chromosomes would eventually lose essential genetic material.

Elizabeth Blackburn suspected that cells might possess a mechanism to rebuild telomeres. Carol Greider joined the search for this enzyme in April 1984. The researchers used Tetrahymena thermophila, a freshwater protozoan with many telomeres, making it ideal for studying chromosome ends.

Greider prepared cell extracts and tested whether enzymes in them could extend artificial telomere DNA. After months of careful experimentation, she observed on December 25, 1984, clear evidence of an enzyme capable of extending telomeres. This enzyme was later named telomerase, and the discovery was published in the journal Cell in 1985. Greider was only 23 years old at the time and had not yet completed her PhD.

Greider completed her PhD in molecular biology at Berkeley in 1987. Later research showed that telomerase contains an RNA component that serves as a template for adding repeated DNA sequences to chromosome ends, thereby maintaining chromosome stability.

Many cancer cells activate telomerase, allowing them to maintain their telomeres and divide indefinitely. Thus, telomerase lies at the crossroads of ageing and cancer.

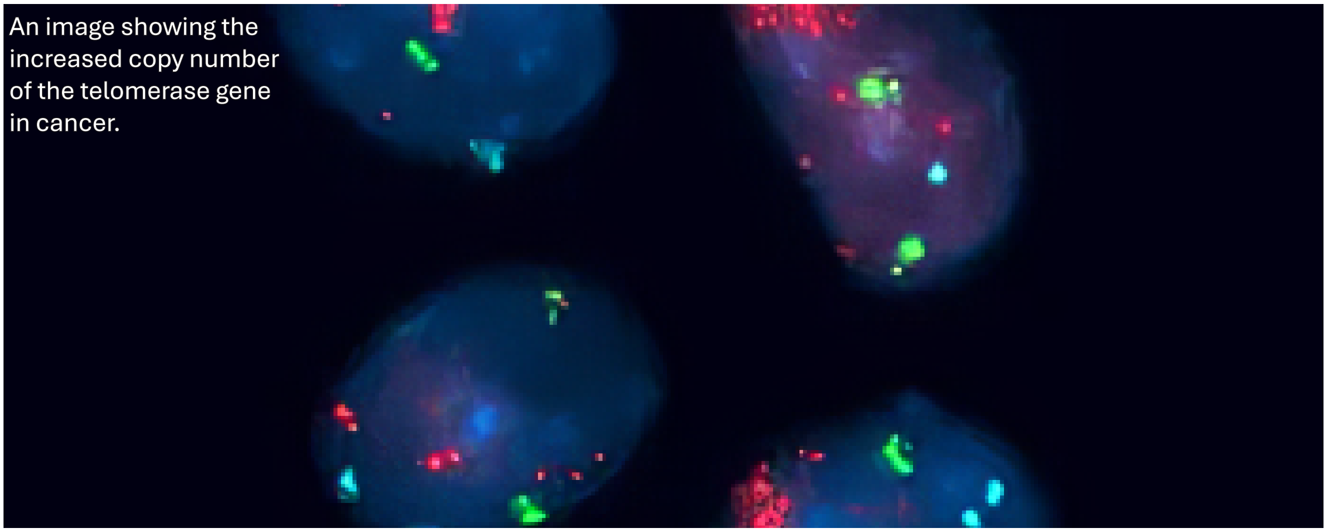
After completing her PhD, Carol Greider established her laboratory at Cold Spring Harbor Laboratory, where she continued studying telomerase and telomere biology. With collaborators, she created the first telomerase-deficient mice, demonstrating that progressive telomere shortening can lead to infertility, tissue degeneration, and premature ageing.

In 1997, Greider joined the Johns Hopkins University School of Medicine, later becoming Director of the Department of Molecular Biology and Genetics. Her research explored telomere biology across organisms—from yeast to mammals—to understand how shortened telomeres trigger cellular responses such as DNA damage signalling.

She was named a Bloomberg Distinguished Professor at Johns Hopkins in 2014, and in 2021 joined the University of California, Santa Cruz, where she continues her research and mentorship.

Greider's work has earned many honours, including the Gairdner International Award, the Wiley Prize, and the Albert Lasker Award. In 2009, she shared the Nobel Prize in Physiology or Medicine with Elizabeth Blackburn and Jack Szostak for discovering how telomeres and telomerase protect chromosomes.

Her journey—from a child struggling with dyslexia to a Nobel laureate—remains a powerful reminder that persistence and curiosity can lead to discoveries that transform science. ◆



An image showing the increased copy number of the telomerase gene in cancer.

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Light in Early Civilisations

Zahid H Khan

From the earliest moments of human history, light has been one of the most powerful and mysterious phenomena in nature. The rising Sun brought warmth, visibility, and life, while darkness often symbolised uncertainty and danger. Long before the emergence of scientific inquiry, ancient people carefully observed the behaviour of light in their daily lives—sunlight casting shadows, reflections appearing in water and polished surfaces, and the colourful arc of the rainbow after rain. These simple yet profound observations inspired myths, philosophical reflections, and the earliest attempts to understand how human beings see the world around them.

Although early interpretations were closely intertwined with religion and cosmology, they represent humanity's first intellectual engagement with optical phenomena. Across different civilisations—Egyptian, Mesopotamian, Indian, Chinese, and Greek—ideas about light gradually evolved from symbolic and mythological explanations to more structured philosophical reasoning and, eventually, early scientific thinking. This long intellectual journey laid the foundation for the systematic study of light that would emerge many centuries later.

Light in Ancient Egypt

One of the earliest recorded understandings of light comes from ancient Egypt (c. 2600 BCE), where observation was deeply connected with religious belief and daily life. The Sun occupied a central place in Egyptian thought and was regarded as the ultimate source of life, warmth, and cosmic order. Light was inseparable from divine power and was personified by the Sun god Ra, whose daily journey across the sky symbolised creation, renewal, and continuity.

Egyptians believed that the gaze of Ra itself produced the light of day. During daylight, Ra illuminated the world, while at night he travelled through the underworld before rising again at dawn. This recurring cycle represented not only the alternation of day and night but also deeper ideas of rebirth and cosmic balance.

During the reign of Pharaoh Akhenaten (c. 1353–1336 BCE), the Sun disk Aten became the central focus of worship. Artistic depictions of Aten show rays extending outward from a circular disk, ending in hands that bestow life upon the Earth. Such imagery suggests an early intuitive recognition that light radiates outward from the Sun and sustains life.

Beyond religious symbolism, the Egyptians also demonstrated practical knowledge of light. Their use of polished metal mirrors indicates an awareness of reflection, even though they did not express it in mathematical terms. Similarly, they carefully observed shadows cast by the Sun. The shadow clock, one of the earliest timekeeping devices, relied on the changing length and direction of a shadow cast by a vertical object. By tracking these changes

Egyptian Sun God 'Ra'

The sun disk 'Aten' worshipped by the Pharaoh Akhenaten

throughout the day, Egyptians could estimate time and monitor seasonal variations.

These observations reveal an implicit understanding of an important optical principle: light travels in straight lines. Although not formally articulated, this empirical knowledge played a significant role in agriculture, architecture, and daily life, particularly in regulating activities linked to the Nile's seasonal cycles.

Light in the Mesopotamian Civilisations

The civilisations of Mesopotamia—especially the Sumerians, Babylonians, and Assyrians—flourished from about 3000 BCE between the Tigris and Euphrates rivers. Their understanding of light combined mythology, cosmology, and systematic observation of celestial phenomena.

The Sun was personified as Shamash (Utu in Sumerian tradition), who was regarded not only as the source of daylight but also as the divine guardian of truth and justice. His journey across the sky symbolised illumination in both a physical and moral sense. Just as sunlight reveals the visible world, Shamash was believed to reveal truth and oversee human actions.

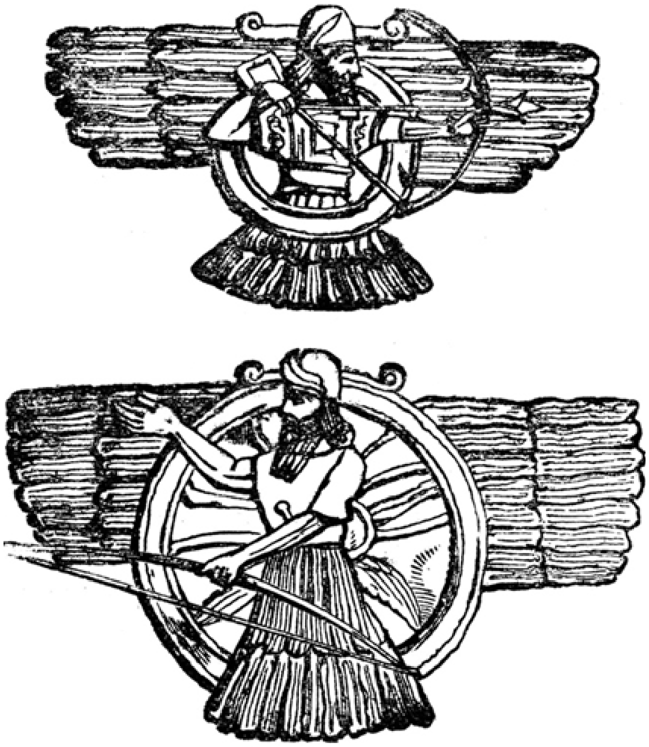
At sunset, Shamash was thought to pass through gates in the western horizon and travel through the underworld, reappearing in the east at dawn. This daily cycle reinforced the idea of cosmic order and renewal. Light thus represented both a natural phenomenon and a moral force, while darkness symbolised uncertainty and the unknown, yet remained an essential part of the cosmic balance.

Mesopotamian scholars also paid close attention to the Moon and the stars. The Moon, associated with the god Sin, played a crucial role in calendar systems. Babylonian astronomers carefully recorded lunar phases, eclipses, planetary motions, and variations in brightness. These observations, preserved on cuneiform tablets, demonstrate one of the earliest systematic studies of celestial light.

In Mesopotamian cosmology, the universe was structured into the heavens, the Earth, and the underworld. Light was associated with the heavens, where luminous bodies moved along predictable paths established by divine order. The regular motion of these celestial sources reinforced the belief in an organised and intelligible universe.

Light and Darkness in Zoroastrianism

Zoroastrianism offers one of the most profound early interpretations of light and darkness, presenting them as opposing cosmic and moral forces. Originating



Mesopotamian Sun God Shamash (Utu)

Ahura Mazda vs. Angra Mainyu

with the teachings of Zarathustra (likely between 1500 BCE and 600 BCE), this tradition associated light with truth, goodness, and divine wisdom, embodied by Ahura Mazda.

Darkness, in contrast, represented falsehood, chaos, and evil, personified by Angra Mainyu (Ahriman). The universe was understood as a battleground between these opposing forces, with the ultimate triumph of light over darkness.

Because of this symbolism, fire and light occupied a central role in Zoroastrian worship. Sacred fires were maintained in temples as visible representations of divine truth and purity. In this tradition, light was not merely a physical phenomenon but a powerful moral and spiritual symbol representing the eternal struggle between good and evil.

Early Chinese Ideas about Light

In ancient China, ideas about light developed within a framework that combined cosmology, philosophy, and systematic observation. The concept of yin and yang played a central role: yang represented brightness, warmth, and activity, while yin symbolised darkness, coolness, and passivity. The alternation of day and night was understood as a manifestation of this fundamental cosmic duality.

Chinese scholars were also careful observers of celestial phenomena. Court astronomers recorded the movements of the Sun, Moon, planets, and stars with remarkable precision. Solar and lunar eclipses were documented as early as the second millennium BCE, and increasingly accurate methods were developed to predict them.

A particularly important contribution came from the philosopher Mozi (c. 470–391 BCE) and the Mohist school. Mohist writings include some of the earliest discussions of optical phenomena, including the idea that light travels in straight lines. They also described image formation through a small aperture, an early explanation of the camera obscura principle.

These ideas reflect a thoughtful combination of philosophical insight and empirical observation. Although not expressed mathematically, they represent an important stage in humanity's effort to understand the behaviour of light.

Ideas about Light in Ancient India

Ancient Indian ideas about light developed within a rich intellectual tradition that combined religious symbolism, philosophical inquiry, and scientific observation. In the *Rigveda,* light is celebrated as a fundamental force sustaining life and cosmic order. The Sun, personified as Surya, was regarded as the supreme source of illumination and vitality and described as the "eye of the gods."

Light in Vedic thought symbolised not only physical illumination but also knowledge and spiritual enlightenment. The daily journey of the Sun across the sky represented the triumph of light over darkness and was closely connected with natural cycles and human life.

Early mythological explanations attributed solar and lunar eclipses to the demon Rahu, who was believed to swallow the Sun or Moon. However, this interpretation was later corrected by the astronomer Aryabhata (476–550 CE). In his work *Aryabhatiya,* he provided a scientific explanation of eclipses as the result of shadows cast by the Earth and Moon. This marked a significant shift from mythological belief to rational and observational understanding.

Aryabhata (476–550 CE)

Light in the Early Greek Era

From Philosophy to Early Science

The Greek approach to light represents a major turning point, marking the transition from mythological explanations to rational and systematic inquiry. Greek thinkers asked fundamental questions about the nature of light and vision: What is light? What is darkness? How do we see?

Different philosophers offered varying interpretations. Anaximander distinguished between sunlight and daylight and even attributed a form of existence to darkness. Pythagoras associated light with goodness and darkness with evil. Empedocles made an important conceptual advance by recognising that darkness is simply the absence of light.

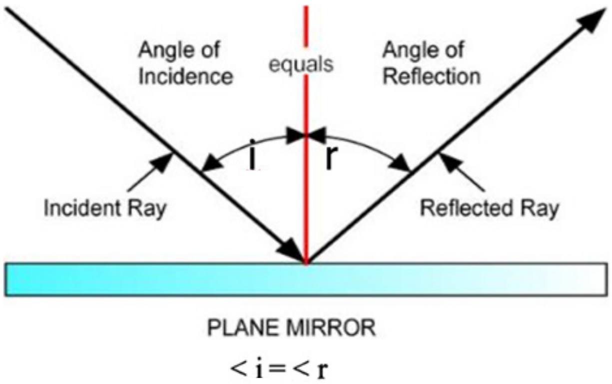
A central debate concerned the mechanism of vision. The emission theory, supported by Empedocles and Plato, proposed that rays emanate from the eyes and interact with objects. Plato described this as a kind of "visual fire" extending outward from the eye.

In contrast, Aristotle proposed the intromission theory, arguing that light originates from objects and enters the eye through a transparent medium such as air. This view was closer to modern understanding and represented a significant intellectual advance.

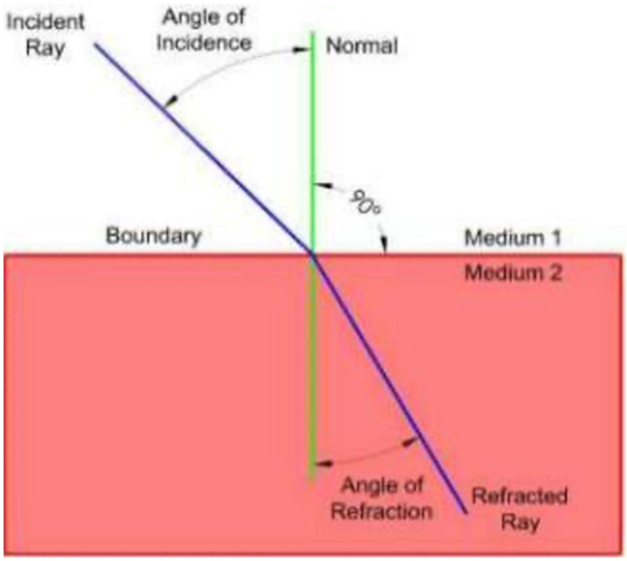
Greek thinkers also recognised the Sun as the primary source of light and explained day and night as natural cycles. Their emphasis on logical reasoning and observation marked the beginning of scientific thinking about light.

Development of Geometrical Optics

Greek scholars further advanced the study of light by introducing mathematical and geometrical methods. Euclid (c. 300 BCE), in his work *Optica,* treated vision in terms of straight-line rays forming geometric patterns. He established two key principles: light travels in straight lines, and reflection occurs such that the angle of incidence equals the angle of reflection.



Reflection of Light from a Plane Mirror



Refraction of Light through a Medium

Although Euclid supported the emission theory, his geometrical treatment of light laid the foundation for the field of geometrical optics.

Claudius Ptolemy (2nd century CE) extended this work through experimental investigations. He studied reflection, refraction, colour, and the geometry of vision. By measuring how light bends when passing from one medium to another, he attempted to determine the relationship between angles of incidence and refraction. Although his results were not entirely accurate, his work represents one of the earliest attempts to combine experiment with theory.

This stage marks a crucial transition in the history of optics—from philosophical speculation to systematic investigation—preparing the way for later developments in the Islamic world and, eventually, modern science. ◆

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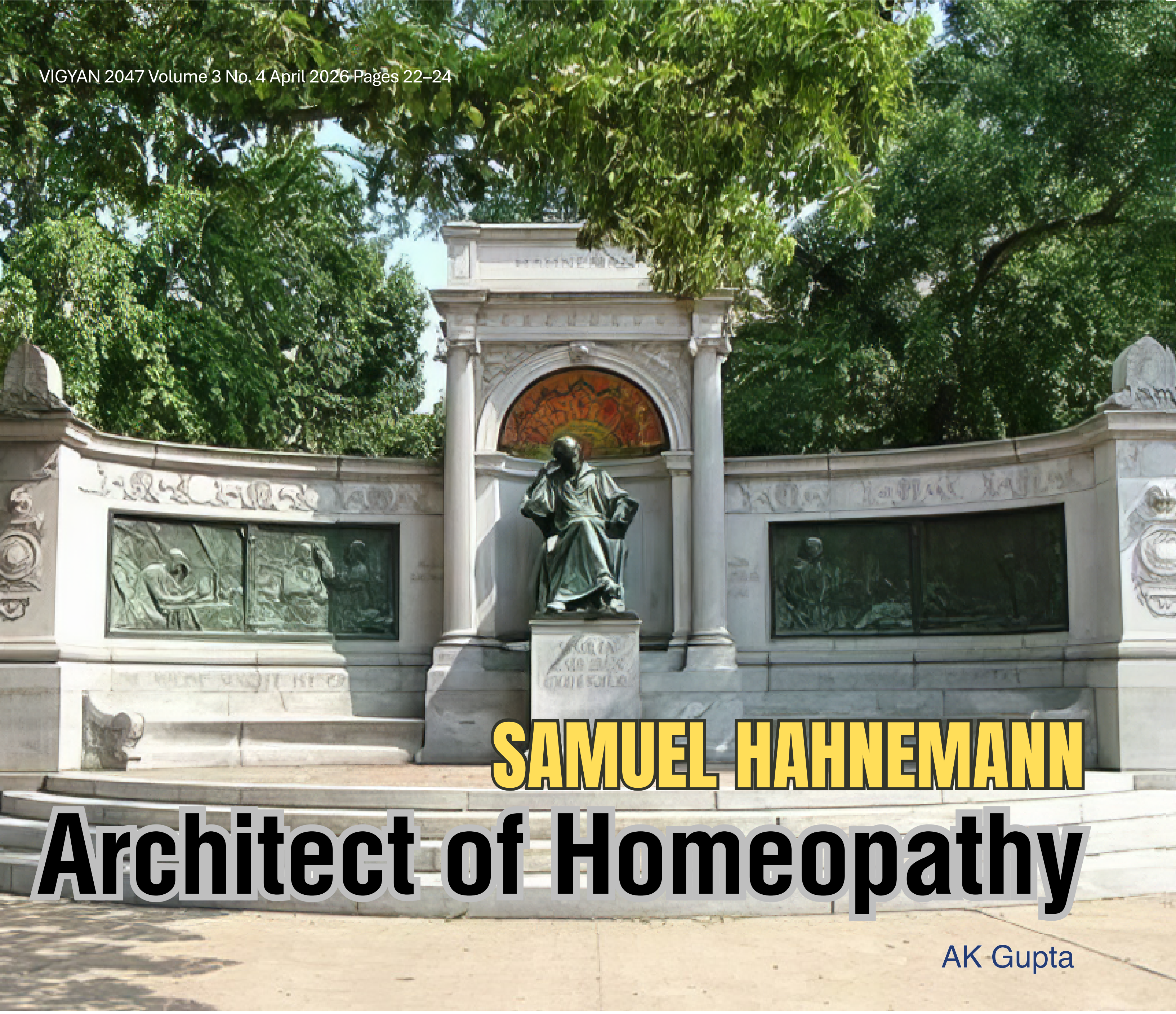

SAMUEL HAHNEMANN
Architect of Homeopathy

AK Gupta

Dr. Samuel Christian Friedrich Hahnemann (1755–1843) occupies a singular place in the history of medicine—a figure who did not merely introduce a new method of treatment but sought to redefine the very philosophy of healing. Trained as a physician and chemist, yet guided by an unusually strong ethical compass, he questioned the prevailing practices of his time and constructed an alternative system that attempted to reconcile science, observation, and compassion.

Born in Meissen, Saxony, into a modest household, Hahnemann's intellectual journey began under circumstances that might have constrained a lesser mind. His father, a porcelain painter, encouraged him not to accept ideas unquestioningly, but to think independently—a formative influence that would later shape his scientific temperament. Even as a boy, his determination to learn bordered on the relentless. An oft-recounted anecdote tells of how he fashioned a small lamp from clay so that he could study at night without drawing his father's attention. This quiet act of defiance reveals a deeper trait: a lifelong refusal to allow external constraints—whether material or intellectual—to limit inquiry.

His brilliance was evident early. By adolescence, he had mastered classical languages and was entrusted by his teachers to instruct fellow students in Greek. Over time, his linguistic command expanded to include several European and Middle Eastern languages, enabling him to access scientific texts in their original form. Financial hardship interrupted his education briefly, forcing him into manual labour at a porcelain factory, yet his teachers

intervened to ensure his return. These formative experiences forged a personality marked by resilience, intellectual rigor, and a refusal to conform to circumstance.

Hahnemann pursued formal medical studies in Leipzig and Vienna, earning his M.D. from the University of Erlangen in 1779. Yet the medical world he entered was deeply troubling to him. Treatments such as bloodletting, purging, and the administration of toxic substances were standard practice, justified more by tradition than by evidence. To Hahnemann, these interventions appeared not only ineffective but often harmful. His discomfort was not merely professional—it was moral. Unable to reconcile his conscience with prevailing methods, he made the extraordinary decision to withdraw from medical practice. This withdrawal was not an abandonment of medicine, but a rejection of what he perceived as its flawed foundations.

During this period, he sustained himself through translation and chemical work. It was here, immersed in the literature of European medicine, that his critical faculties sharpened. The turning point came in 1790 while translating a text by William Cullen. Skeptical of Cullen's explanation of cinchona bark's effectiveness against malaria, Hahnemann chose to investigate personally. By ingesting the substance himself, he experienced symptoms resembling the disease it was said to cure. This self-experimentation—remarkable for its boldness—led him to a principle that would define his life's work: that substances capable of producing symptoms in healthy individuals might cure similar symptoms in the sick.

This insight was not treated as an isolated curiosity. Hahnemann pursued it systematically, conducting repeated experiments and refining his observations. The principle of "like cures like" became the foundation upon which he constructed a comprehensive medical system. What distinguishes his work is not merely the idea itself, but the method by which he elaborated it—through disciplined observation, documentation, and synthesis.

He introduced the practice of testing substances on healthy individuals to observe their effects, a process he termed "proving." This approach, grounded in direct human observation rather than theoretical speculation, represented a significant departure from the norms of his time. He also advanced the idea that medicines should be administered in minimal doses, not only to reduce harm but to enhance therapeutic effect. While this concept would later become a point of contention, it was rooted in his broader commitment to minimizing intervention and avoiding the excesses of contemporary medicine.

Equally central to his thinking was the notion of a vital force—a dynamic principle governing the human organism. Disease, in his view, was not merely a physical

He introduced the practice of testing substances on healthy individuals to observe their effects, a process he termed "proving." This approach, grounded in direct human observation rather than theoretical speculation, represented a significant departure from the norms of his time.

malfunction but a disturbance of this underlying equilibrium. This perspective led him to focus on the totality of symptoms rather than isolated manifestations, emphasizing individualized treatment long before such approaches became widely accepted.

Hahnemann's ideas extended beyond theory into practice. His treatment of patients reflected a markedly different ethos—one that prioritized dignity, gentleness, and careful observation. An illustrative episode from his career involved the treatment of a mentally ill nobleman, Prince Klockenbring. At a time when such patients were often subjected to harsh confinement, Hahnemann advocated for humane care, treating the condition as a medical issue rather than a moral failing. This approach anticipated later developments in psychiatry and underscored his broader commitment to ethical medicine.

The persuasive power of his methods is perhaps best illustrated by the case of Constantine Hering. Initially tasked with disproving homeopathy, Hering approached the system as a skeptic. Yet through experimentation and personal experience, he became convinced of its validity and emerged as one of its most influential advocates. Such transformations were not uncommon among those who engaged seriously with Hahnemann's work, suggesting that his ideas possessed an experiential dimension that extended beyond theoretical argument.

In 1810, Hahnemann published the Organon of Medicine, a work that articulated his philosophy with clarity and precision. The Organon was not simply a manual of treatment; it was a comprehensive framework addressing the nature of disease, the role of the physician, and the principles of therapeutic intervention. Its successive editions reflect an evolving thinker, continually refining his ideas in response to experience.

In 1810, Hahnemann published the Organon of Medicine, a work that articulated his philosophy with clarity and precision. The Organon was not simply a manual of treatment; it was a comprehensive framework addressing the nature of disease, the role of the physician, and the principles of therapeutic intervention.

Despite the coherence of his system, opposition was fierce. Apothecaries resisted his insistence on preparing his own medicines, while many physicians dismissed his methods as unscientific. Hahnemann responded not with retreat but with conviction, defending his principles both in writing and in practice. His oft-cited remark—that it is better to give nothing than to give poison—captures the ethical stance that underpinned his entire approach.

In his later years, Hahnemann relocated to Paris, where his work achieved broader recognition. There, he established a successful practice and attracted patients from across Europe. An unexpected personal chapter unfolded when he married Mélanie d'Hervilly, a French artist significantly younger than himself. Their partnership brought renewed energy to his work and contributed to his prominence in Parisian society.

Even in old age, Hahnemann remained intellectually active, continuing to refine his theories and treat patients. His final reflections reveal a man who viewed his life not in terms of achievement but of duty fulfilled. His reported words—expressing gratitude rather than entitlement—offer a glimpse into the philosophical humility that accompanied his intellectual boldness.

Hahnemann's legacy resists simple categorization. His system has been embraced by millions and institutionalized in various parts of the world, while also remaining the subject of ongoing scientific debate. Yet beyond agreement or disagreement, his broader contributions are clear. He challenged medicine to reconsider its methods, to prioritize the patient as an individual, and to temper intervention with caution. He demonstrated that innovation often arises not from acceptance of established knowledge, but from the courage to question it.

What endures most is not merely the system he created, but the spirit in which he created it—a commitment to inquiry, an insistence on ethical responsibility, and a belief that medicine must ultimately serve the well-being of the individual. In this sense, Hahnemann's work continues to resonate, inviting each generation to re-examine the foundations of healing and the principles that guide it. ◆

***Dr AK Gupta** is a profound homoeopathic practioner and founder director of AKGsOVIHAMS. He can be reached at drakgupta@ovihams.com*

Sreedher Ramamurthy: Community Radio Man of India

Dr. Ramamurthy Sreedher, often hailed as the "Father of Community Radio in India," is a veteran broadcaster whose career spans over five decades in radio and television. His work has been instrumental in shifting the focus of Indian broadcasting from centralized information to grassroots community engagement, particularly through science communication and educational media.

Sreedher's most significant legacy is the establishment of India's first community radio station, Anna FM, at Anna University in Chennai on February 1, 2004. This milestone marked the beginning of a movement that decentralized airwaves, allowing local communities to produce content in their own dialects and address regional issues.

Visionary Leadership: He served as the Director of the Commonwealth Educational Media Centre for Asia (CEMCA) from 2007 to 2012, where he worked with the Ministry of Information and Broadcasting to expand community radio into "dark districts" where no stations previously operated.

Grassroots Impact: He defines community radio as "radio of the people, by the people, and to the people". His efforts helped grow the sector from a single station to over 480 stations as of early 2024, serving farmers, tribal groups, and coastal communities.

Sreedher's background in chemistry—holding a PhD from Madras Christian College—deeply influenced his approach to broadcasting. He viewed radio as a "laboratory" for making complex scientific concepts accessible to rural populations.

Mass Outreach: He produced some of the world's largest radio serials, including one for children broadcast in 18 languages. His science serials, such as Vigyan Vidhi, Radio DATE (Drug Alcohol Tobacco Education), and Manav Ka Vikas, reached nearly 140,000 registered learners in the pre-digital era.

Bridging the Gap: As a science reporter for All India Radio, he brought scientists directly to villages to discuss daily concerns like agriculture and healthcare, ensuring science was relevant to the lives of rural inhabitants.

Beyond community radio, Sreedher was a primary architect of India's national educational broadcasting infrastructure:

Gyan Darshan: Visionary behind India's first 24x7 educational television channel.

Gyan Vani: Architect of the first educational FM radio station.

Open Learning: At IGNOU, he played a pivotal role in institutionalizing internet radio (Gyandhara) to support distance learners.

In 2026, the Government of India conferred the Padma Shri upon Dr. Sreedher for his lifelong service to radio broadcasting and public service. He has also received life-time achievement awards from international bodies like the AIBD (Asia-Pacific Institute for Broadcasting Development).

Currently, as a Professor Emeritus at Apeejay Stya Univer-sity, he continues to innovate through "Radio Stya Vani" and projects like "Anubhav," an online podcast series specifically for senior citizens. ◆

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Soviet Science to Global Rankings: Central Asia’s STEM Transformation

Nakul Parashar

From the launchpads of Baikonur Cosmodrome to the classrooms of Nazarbayev University, L. N. Gumilyov Eurasian National University, Satbayev University, and Kazakhstan-British Technical University (KBTU), Central Asia’s STEM story is one of legacy meeting ambition.

Central Asia today stands at a compelling intersection of history and aspiration in the domain of STEM education. The region’s higher education systems are shaped by a powerful Soviet-era legacy of scientific rigor, now undergoing a rapid transition toward globally aligned, innovation-driven models. This transformation reflects a broader reorientation of national priorities, where economies are increasingly being structured around knowledge systems, technological capability, and research-led growth.

The intellectual foundations of STEM in Central Asia extend back to centuries of knowledge exchange along the Silk Route, linking the region with civilizations such as India, Persia, and the Arab world. Yet, it was during the Soviet period that this tradition was formalized into one of the most rigorous scientific ecosystems of the twentieth century. Central Asia became an integral part of a vast knowledge network that supported advances in aerospace, nuclear science, geophysics, and engineering.

New Uzbekistan University, Tashkent

KBTU, Almaty

Astana, Kazakhstan

LN Gumilyov Eurasian National University, Astana

Satbayev University, Almaty

An often underappreciated dimension of this scientific ecosystem was its deep influence on India's own STEM education landscape. For several decades—particularly from the 1960s until the late 1980s—Soviet scientific literature, especially through Mir Publishers, played a transformative role in shaping generations of Indian students. Affordable, high-quality textbooks in physics, mathematics, engineering, and computer science were widely available across Indian universities and book markets. Titles on advanced calculus, theoretical physics, mechanics, and electronics became standard references for students preparing for engineering and scientific careers.

These books were not merely instructional—they reflected a pedagogical philosophy rooted in conceptual depth, problem-solving rigor, and mathematical precision. For many Indian students of that era, Mir publications provided access to global-quality scientific knowledge at a fraction of the cost of Western texts. This intellectual bridge fostered a quiet but enduring academic connection between India and the Soviet scientific ecosystem, including Central Asia. Even today, many senior engineers, scientists, and academicians in India recall Mir textbooks as foundational to their academic training.

At the core of Central Asia's academic strength lies its enduring emphasis on theoretical physics and mathematics, disciplines that formed the backbone of Soviet science. Universities across Kazakhstan, Uzbekistan, and neighboring republics were designed to produce specialists capable of solving complex scientific problems across strategic sectors. This emphasis on abstraction, modelling, and analytical reasoning continues to define the region's academic culture.

Few symbols capture this legacy as powerfully as the Baikonur Cosmodrome. As the world's first and largest operational space launch facility, it represents the culmination of decades of investment in fundamental and applied sciences, placing Central Asia firmly within the global history of scientific achievement.

This tradition is sustained by institutions such as Al-Farabi Kazakh National University, ranked #166 globally in QS World University Rankings 2026, with over 20,000 students, and National University of Uzbekistan, one of the region's oldest academic centers. In the QS Asia Rankings 2026, L. N. Gumilyov Eurasian National University ranks 61st, while Satbayev University stands at 79th, placing both among Asia's top 100 institutions.

The modern phase of transformation is led by institutions such as Nazarbayev University, ranked in the 401–500 band globally (THE 2026), which has rapidly established itself as a research-intensive university with strong international collaborations and English-medium programmes.

A defining feature of this transition is the widespread adoption of English as a medium of

Continues on page 31


Nazarbayev University, Astana
#1 in Central University: THE Ranking

India–Central Asia Student Mobility: A Strategic Opportunity

The evolving academic landscape of Central Asia presents a timely opportunity to deepen educational linkages with India through a structured student mobility strategy. Given geographical proximity, historical academic connections, and complementary strengths, a focused approach can create a mutually beneficial education corridor.

A first priority lies in institutional partnerships. Leading Central Asian universities—such as Nazarbayev University, L. N. Gumilyov Eurasian National University, and Satbayev University—can collaborate with Indian institutions for joint degrees, credit transfer frameworks, and dual supervision of research. This would enhance academic mobility while ensuring quality assurance and global recognition.

Second, targeted programme alignment can significantly improve student flows. Central Asia offers strong opportunities in engineering, medicine, data science, energy systems, and sustainable infrastructure—areas that align well with India's demand for globally trained STEM graduates. Structured pathways for undergraduate and postgraduate admissions, supported by transparent fee frameworks and standardized entry criteria, can further streamline access.

Third, scholarship and financing mechanisms will play a critical role. Bilateral or multilateral scholarship schemes, combined with institutional fee support and education loans, can make Central Asian universities more accessible to Indian students. This can be complemented by industry-sponsored fellowships in sectors such as energy, transport, and digital technologies.

Fourth, the expansion of English-medium programmes and student support services should be leveraged more actively. As universities in the region increasingly adopt English for instruction, targeted outreach—through digital campaigns, academic fairs, and partnerships with Indian institutions—can enhance awareness and trust among prospective students and their families.

Fifth, there is a strong case for developing mobility ecosystems rather than isolated admissions pipelines. This includes internship linkages with regional industries, research collaborations, and post-study work opportunities. Such an integrated approach would position Central Asia not merely as a study destination, but as a platform for career development and international exposure.

Finally, policy-level engagement between governments can further strengthen this corridor through visa facilitation, mutual recognition of qualifications, and academic exchange frameworks. Given the historical academic connections—once shaped by shared scientific resources and intellectual exchange—this emerging mobility can be seen as a natural evolution into a more structured and contemporary partnership.

April 2026

Yakolovs and Irodovs ruled IIT-JEEs

The strength of science and mathematics education in the erstwhile Soviet Union remains one of the most influential educational models of the twentieth century. It was not simply a system of teaching, but a carefully designed intellectual framework aligned with national priorities—industrial growth, scientific leadership, and technological self-reliance. The Soviet state invested heavily in building a culture where science and mathematics were not optional pursuits but central to societal progress.

At the heart of this system was a deep emphasis on theoretical rigor and conceptual clarity. Mathematics was treated as the foundation of all scientific inquiry. Students were trained to think abstractly, solve complex problems, and derive results from first principles. Subjects such as algebra, calculus, and geometry were taught with remarkable depth, often far beyond what was typical at comparable levels elsewhere. Physics education followed a similar approach, focusing on fundamental laws and their applications across real-world phenomena.

A defining feature of Soviet pedagogy was its ability to combine simplicity with depth. Textbooks were crafted not merely to inform but to train the mind. *High School Mathematics* by G. N. Yakolov (often circulated in English translations and similar Soviet compilations) became widely respected for their structured approach and graded problem sets. In physics, few books achieved the iconic status of Problems in General Physics by I. E. Irodov, popularly known among students as “Irodov.” This book, with its challenging numerical problems, became a benchmark for serious learners, demanding not just understanding but mastery of physical concepts.

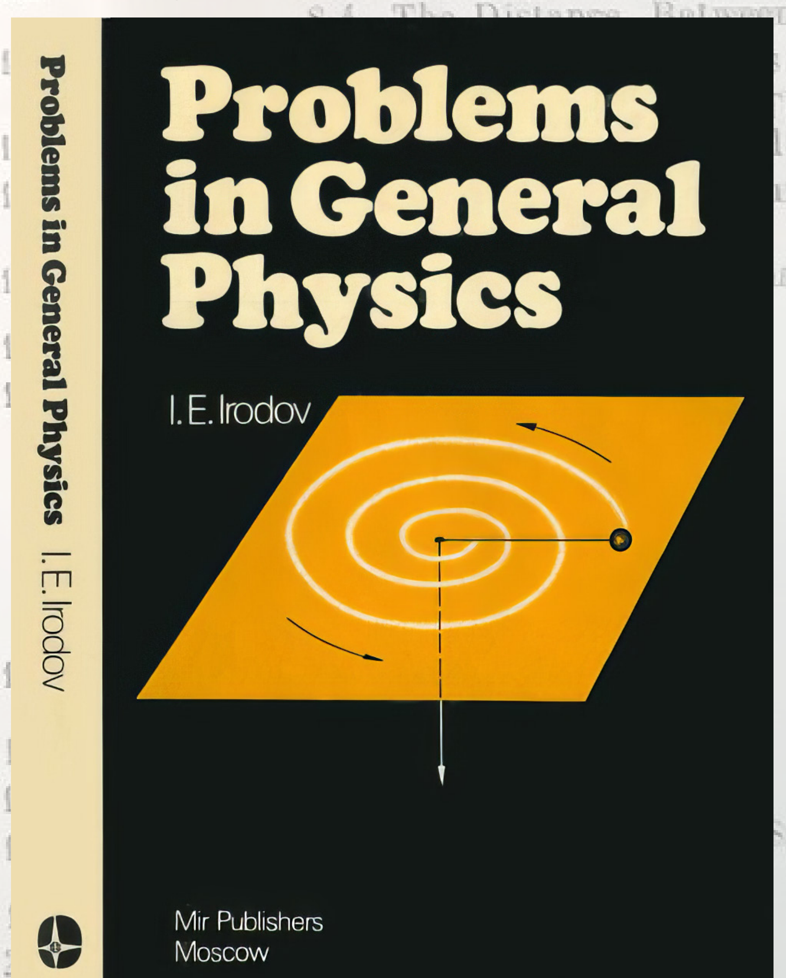
In India, the impact of Soviet science education—mediated through Mir publications—was profound. From the 1960s until the late 1980s, these books were widely available in Indian bookstores and academic institutions. For many students, especially those in engineering colleges and universities, they became essential learning resources. Titles on advanced mathematics, mechanics, electronics, and theoretical physics were used not only as supplementary reading but often as primary texts.

Books like Irodov’s problem sets became almost a rite of passage for serious physics students in India. They were extensively used by aspirants preparing for competitive examinations such as the IIT-JEE, where conceptual depth and problem-solving ability were critical. Similarly, Soviet mathematics texts—whether authored by Yakolov or others in the same tradition—helped students develop a disciplined approach to problem-solving, emphasizing logic over rote learning.

Moreover, this intellectual exchange fostered a subtle but significant alignment between Indian and Soviet (including Central Asian) approaches to STEM education. The shared focus on mathematics and theoretical sciences created compatibility in academic frameworks, which continues to have relevance in contemporary collaborations.

The Soviet system also institutionalized talent identification through Olympiads, specialized schools, and research-linked universities. This ensured a continuous pipeline of high-quality scientific talent, capable of contributing to ambitious national projects such as space exploration and nuclear research.

In retrospect, the Soviet model—and its transmission through institutions like Mir Publishers—played a crucial role in strengthening the foundations of science and mathematics education in India. The legacy of books like Yakolov’s mathematics texts and Irodov’s physics problems continues to endure, not just as academic resources, but as symbols of a pedagogical philosophy that valued depth, clarity, and rigor above all else.



instruction, particularly in leading institutions such as Kazakhstan-British Technical University (KBTU). This shift is enabling deeper global integration, attracting international faculty, and facilitating student mobility.

Simultaneously, Central Asia is investing heavily in world-class academic infrastructure—modern campuses, advanced laboratories, digital ecosystems, and research parks. These developments are bridging the gap between the region's strong theoretical foundation and the demands of applied, innovation-driven education.

For students from India, Central Asia presents a compelling academic destination. Its geographical proximity, cultural familiarity, affordability, and increasing availability of English-medium programmes make it particularly attractive. This is complemented by growing institutional partnerships, improved connectivity, and streamlined admission processes. In many ways, the historical academic linkages—once mediated through Soviet-era knowledge flows such as Mir publications—are now evolving into direct educational mobility and collaboration.

Across the region, countries such as Uzbekistan, Kyrgyzstan, and Tajikistan are also strengthening their STEM ecosystems through curriculum reforms, infrastructure development, and international engagement. Universities like Tashkent State Technical University and Tajik Technical University are gradually aligning with global standards.

Despite this progress, challenges remain—particularly in research funding, faculty retention, and aligning academic output with industry needs. However, increasing emphasis on innovation ecosystems, incubation centres, and applied research is helping address these gaps.

What emerges is a region undergoing a thoughtful transformation—retaining its intellectual rigor while embracing global standards and technological change. Central Asia is not merely catching up; it is repositioning itself within the global STEM landscape.

From the enduring legacy of Mir Publishers to the modern research ecosystems of its leading universities, the region represents a continuum of scientific tradition and contemporary ambition.

The future of STEM in Central Asia will depend on how effectively it continues to integrate theory with application, scale with quality, and regional strengths with global engagement. In that balance lies its potential to emerge as a significant scientific and educational hub in the decades ahead. ◆

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Green Tribology Towards Sustainability

Kamal Mukherjee

Dr. H. Peter Jost is known to the international tribology community as the father of the subject—**"the man who made the world spin a little easier".** He was the author of the famous 'Jost Report', where he coined the term "tribology" in 1966 to combine the application of friction, wear & lubrication in UK industry. Over the following five decades, up to his death in 2016, he was tireless in extolling the importance of tribology to manufacturing efficiency, energy conversion and environmental sustainability. Dr. Zhang (Zhang, 2009) coined the word "Green Tribology" for first time. "Green" is representative of thoughts on ecological balance with protection of environment so as to achieve the sustainable developments in nature vis-s-vis bring harmony in the society—it connotes quality of life. Thus "Green Tribology" is the ***'science of green or environment-friendly tribology which deals with tribological aspects to balance the ecology, environment and biological impacts of interacting surfaces in relative motion'.*** Then it was popularised globally by Dr. H. Peter Jost, president of the International Tribology Council, at 4th World Tribology Congress in 2009. Dr. Jost in 2010 at Moscow seminar said ***"the cause of Green Tribology is indeed a worthy cause for all tribologists and their organizations to pursue, as it will help tribology to play its rightful part, not only for the benefit of science and technology, but much more importantly, for the benefit of mankind."***

Importance of green tribology

Nowadys, "green tribology" has become part of the engineering dictionary. Emilia Assenova et al in their 2012 conference paper "Green tribology and quality of life" showed the important point: ***"Nowadays, losses resulting from ignorance of tribology amount to about 6% of the gross national product (GNP) in the United States alone. This figure is around USD 900 milliard annually. As far as China is concerned, they could save above USD 40 milliard per year by the application of tribology or more than 1.5% of the GNP."***

Green Tribology has become critical in today's context of continuous imposition of a "double-edged sword"—firstly the natural resources are depleting as we are consuming it for more & more industrialization & secondly the resources vis-à-vis the whole planet is continuously being polluted with the contaminants! We as a human being

& technocrats have a moral responsibility to save our mother Earth. Thus, its relevance goes beyond merely to get the better efficiency but it has an impact to control the greenhouse gas emissions for attaining sustainable development (a big word highlighted nowadays). Drs. Kenneth Holmberg and Ali Erdemir highlighted that ***"a significant portion of global energy consumption is attributed to inefficiencies in tribological contacts"*** & said ~23% of current global energy consumption arises from tribological inefficiencies as approximately 30% is spent on addressing friction issues, while the remaining 3% is allocated to remanufacturing worn parts and spare equipment due to wear and wear-related failures. The stakes are high, but so too are the potential benefits. Embracing Green Tribology could lead to substantial energy savings and a notable reduction in carbon emissions. The savings, particularly prominent in transportation and power generation, offer not only environmental benefits but also significant economic advantages (*Influence of Tribology on Global Energy Consumption, Costs, and Emissions, 2017*).

Green tribology: Principles & Challenges

Nosonovsky & Bhushan (in 2010) have combined green tribology, green engineering and green chemistry into 12 principles: the minimization of (i) friction and (ii) wear, (iii) the reduction or complete elimination of lubrication, including self-lubrication, (iv) natural and (v) biodegradable lubrication, (vi) using sustainable chemistry and engineering principles, (vii) biomimetic approaches, (viii) surface texturing, (ix) environmental implications of coatings, (x) real-time monitoring, (xi) design for degradation, and (xii) sustainable energy applications. The three areas of green tribology: (i) biomimetics for tribological applications, (ii) environment-friendly lubrication, and (iii) the tribology of renewable-energy application e.g. solar, wind & ocean energy. The integration of these areas remains a primary challenge for this novel area of research.

Bio-Mimetics Design for Tribological Applications

In order to find the solutions to technical challenges, superior marvels have been found throughout the living nature continually e.g. skin from fast-swimming sharks intrigue researchers as its low-drag riblet microstructure is applicable to many low drag and self-cleaning (antifouling) applications. Riblets are bio-inspired replications of fast-swimming sharks that acceptably mitigate friction or viscous drag through the surface. Some conventional shapes of riblet geometries are illustrated in Fig-1. In one application the unique anti-drag properties of shark skin known as the Riblet effect has successfully been used in the design of the wing skin of Airbus aircraft leading to a 6% reduction in air drag and significant savings in fuel costs. Moreover, riblets show promise for adaptation to various flow control applications for drag reduction, such as aviation, marine ships, automotive, wind energy, sports etc. In 2010, the BMW Oracle team won the 33rd America's Cup with their racing yacht covered with riblets in 2012, riblets found their applications on wind turbine blades & a Formula-1 car by bionic surface technology.

Application of Bio-Lubricants

Our earlier civilization was using the vegetable oil for creating a lubrication while pulling the heavy objects e.g. statue of Pharaoh (~3000 years ago), sled traction etc., these oils were made from the organic source so may be regarded a first bio-lubricant. The Mineral oils

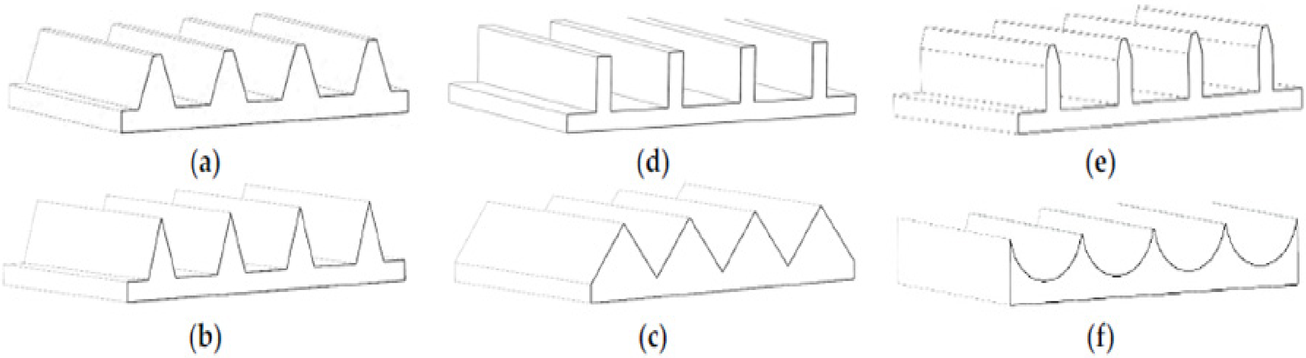

Fig-1: Conventional riblet geometries: (a) trapezoidal, (b) spaced triangular, (c) triangular, (d) bladed, (e) trapezoidal bladed, and (f) semi-circular

are used since late 18th century & derived from non-renewable fossil sources which is none bio-degradable. Combustion engine uses extensively of this mineral oil for lubrication. Creating a bio-lubricants from bio-mass waste materials would be towards sustainable approach. However, for a typical application like wind turbine, to get a bio-lubricant is really challenging. Vegetable oils as green liquid lubricants e.g. avocado, canola (rapeseed), corn, olive, peanut, safflower, sesame, and vegetable oil were used by changing their structural and chemical properties have been studied for their tribological performance as 2-stroke & 4-stroke engine oil, hydraulic oil, metal cutting fluids, additives etc. (Tribology of Green Lubricants by Satish Kailas et al, Ch-14, in Tribology for Scientists and Engineers, 2013)

Contribution of Tribology for Sustainability

According to the World Commission on Environment and Development (WCED) of the United Nations definition of sustainability under the title 'Our Common Future' is ***"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own need"*** (World Commission on Environment and Development, 1987).

"It is indicative that socio-cul¬tural, ecological and economical resources are to be consumed and utilized such that it is left available in equal quality and quantity to future generations". However, it is not being practiced now. In the era of rapid development of industry, agriculture, science and technology, the population growth, comfortable life style, incipient needs etc. all ultimately increases the consumption of primary energy resources. Thus, there is a need to shift the focus from only economic to the ecology balance. As far as wear protection is concerned, tribology fits in well with sustainability as cross-sectional challenge. The sustainability can be achieved by three following strategies:

1) Efficiency strategy: 1st priority should be given to the consumption of primary energy and resources & must not be compromised on the plea of economic development.
2) Consistency strategy: a) "Waste not want not" should be the culture i.e. controlling the waste generation, b) waste should be digested by the nature i.e. biodegradable, recyclable, renewable etc. c) compatibil¬ity of anthropogenic material and energy flows with nature. Anthropogenic hazardous particulate matters (AHPM) refer to small airborne particles generated by human activities these are detrimental to the human health as it can enter through the respiratory tract so once inhaled, goes to the root of respiratory tract, mixes with the bloodstream thus causing heart & lungs related diseases.
3) Sufficiency strategy: To augment the resource efficiency, one of the key features of tribology i.e. the wear protection contributes a lot towards sustainable development goals so its economic significance of wear must not be underestimated. Strict compliance must be enforced right at the initial stage, R&D, production and utiliza¬tion of all products improvements and inventions.

Sustainability and lubricants

In 1990, the first environ¬mentally compatible lubricants were marketed. But market acceptability was hardly 3% to 4% even after passing of 30 years! The main reason was none availability & higher prices of compliant base oil & additives fulfilling the eco-toxicological criteria. Lubricants based on biomasses or renewable raw materials benefit from the same functional profile as petrochemical products, but with distinctly better environmental balance. Sustainable

Fig-2: Sustainable development goals of the United Nations directly related to tribology

lubricants based on the 17 SDGs of the United Nations feature the following benefits:

a) Friction reductions lower CO_2 emissions (energy efficiency).
b) Extended oil change intervals reduce waste and the consumption of resources.
c) Base oils and additives based on renewable raw materials lower the consumption of re-sources on CO_2-neutral basis (solutions: es¬ters, polyalkylene glycols and bio-olefines).
d) Fast bio-degradability combined with low toxicity for flora, fauna and life.
e) Complete waste oil collection with a material recycling concept.

Sustainable development goals of the United Nations

Tribology affects seven out of the 17 sustainability development goals (SDG) and the wear protection directly covers many of the SDG-targets e.g. §8, §9 and §12: ***"Ensure sustainable consumption and pro¬duction patterns. Here, tribology can make a tremendous impact through wear protection: Using products longer saves resources of any kind".*** Bio-lubricants meet the expectations of SDGs §3, §6 und §12 (Fig-2). The tonnage of lubricants corre¬sponds to about 1% of the fuel volume.

Thus, focus of green tribology is to make the process of friction and wear as environmentally friendly as possible so it's an interdisciplinary area of science & technology which includes energy, materials science, green lubrication, and environmental science etc. Thus, it takes care of the manufacturing processes, minimises friction and wear, takes care of human health finally reduces the burden on the planet. The sustainability has already become a vital goal globally in every forum. Hence, real sustainable development is achieved if *"Development which meets the needs of the current generation without compromising the future generation to meet their own needs."* ◆

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The Wild Mathematics of Modern War

Abhijit Dasgupta

Imagine, you're in a room with computers around ... guarding a city. Suddenly radar screens light up—you hear a ping!

A small flying object is coming your way—buzzing through the night sky like an angry scooter with wings.

You press the defence button.

WHOOSH. A missile shoots up and destroys it.

The crowd cheers. You smile—satisfied.

But there is always criticism.

Someone whispers the bill.

The drone cost about ₹30 lakh.

The missile that destroyed it cost ₹80 lakh.

Victory? Yes. Good bargain? Not exactly.

Welcome to the strangest math problem in modern warfare.

You've read about the Japanese Kamikaze—the zero fighters diving to destroy ships ... never to return. Meet the 'modern times'—"Flying Kamikaze."

One of the most talked-about drones today is the Shahed-136.

It's not a sleek fighter jet. It's not supersonic. In fact, it's slow enough that some people say it sounds like a lawnmower that learned to fly.

But that's exactly the point. It is designed to be, simple, cheap and disposable.

The drone flies toward its target and crashes into it exploding on impact.

Because it never needs to come back, engineers can make it far cheaper than traditional aircraft.

Most estimates say such drones cost roughly $20,000–$50,000.

That's roughly the price of a luxury car.

Which is surprisingly cheap for a weapon that can travel hundreds of kilometers.

It is the Defender's Problem.

Now imagine you are defending against that drone.

You rely on a famous system called Iron Dome.

To destroy the incoming threat, the system launches a Tamir interceptor missile.

Each interceptor costs somewhere around $40,000–$100,000.

Which creates a strange situation.

It's like trying to stop a paper aircraft with a diamond-tipped arrow.

The arrow wins. But your wallet loses.

The birds taught—no not in a class, in the sky. Now here's where things get really interesting.

Imagine one drone. Not too scary. Now imagine 60 drones arriving at once.

This actually happens in modern conflicts.

The idea of drone swarms comes straight from nature. Scientists watching flocks of birds noticed something remarkable—no leader, just simple rules—stay close, match direction, don't crash. Yet thousands move like one living cloud. Scientists watched, noticed and transformed this "swarm intelligence" for warfare. Instead of one expensive drone, launch hundreds of cheap ones that talk to each other and adapt. Lose a few? No problem, the swarm keeps going. Air defences built for big missiles suddenly face a buzzing cloud of tiny attackers. In short, modern warfare has borrowed a trick from nature—don't be a lone tiger—be a swarm of bees. And remember, even giants jump when bees sting.

Let's do the math.

Attacker launches 60 drones.

Cost: 60 × $30,000 ≈ $1.8 million

Defender fires 60 interceptors.

Cost: 60 × $50,000 ≈ $3 million

So, the defender spends almost twice as much money stopping the attack.

It's like someone throwing cheap tennis balls, while you defend yourself with gold-plated cricket bats. But There's a Catch.

Before we start feeling sorry for the defender, remember something important.

If even one drone slips through, it might hit—an oil refinery, an airport, a power station, a crowded hospital building.

The damage could easily reach hundreds of millions of dollars.

Suddenly that $50,000 missile starts looking like a very smart investment.

Here's the funny part. Iron Dome is already considered one of the cheaper missile defense systems in the world.

Some interceptors designed to destroy ballistic missiles cost several million dollars each.

Those missiles travel faster than a rifle bullet, sometimes even faster than sound many times over.

Stopping them is like trying to hit a bullet with another bullet.

So, against those threats, expensive interceptors make sense.

But drones are different.

They are slow, cheap, and easy to mass-produce.

And that changes everything.

Instead of launching one expensive missile, attackers may launch hundreds of cheap drones.

This is called a swarm attack.

The idea is simple.

Even if most drones are destroyed, the defender might run out of interceptors, spend huge amounts of money, get overwhelmed resulting in panic.

It's like facing a hundred mosquitoes instead of one tiger.

The tiger is more dangerous. But the mosquitoes are far more annoying.

Modern air-defence systems are smarter than you might think.

In The Birds, directed by Alfred Hitchcock, ordinary birds suddenly begin attacking humans in coordinated waves. One bird is harmless. A hundred arriving together becomes terrifying. The fear comes from numbers, unpredictability, and attacks from all directions, exactly the logic behind modern drone swarms.

But how did Hitchcock imagine such a nightmare?

Interestingly, the film was inspired by a short story by Daphne du Maurier. Around the early 1960s there were also real news reports of seabirds behaving strangely along the California coast, possibly after eating toxic algae. Hitchcock loved turning ordinary things into threats, showers, staircases, trains and the idea of nature itself turning hostile fascinated him.

So, he took something completely familiar—birds in the sky and asked a chilling question: *What if they attacked together?*

Modern drone swarms follow a similar logic. One drone can be shot down easily. But dozens or hundreds moving like a flock, communicating through algorithms, can overwhelm defences. Even if many are destroyed, others slip through, like a cloud of mechanical starlings.

In a strange way, Hitchcock imagined the psychology of swarm warfare long before engineers built it. His birds were not machines but the terrifying idea of many small attackers acting as one mind was already there.

Engineers borrowed logic from nature and human reflexes—like a hawk predicting a bird's flight or a cricket fielder judging where the ball will land.

Iron Dome is Israel's smart shield against short-range rockets. Radar spots a launch, computers instantly calculate the rocket's path, and if it threatens a town, a Tamir interceptor shoots up and blows it apart mid-air. If it's heading for open land, the system ignores it—saving money.

Engineers borrowed logic from nature and human reflexes—like a hawk predicting a bird's flight or a cricket fielder judging where the ball will land. Fast radar, clever algorithms and guided missiles together create a rapid, automated "reflex" that protects cities.

Iron Dome doesn't shoot at everything. Computers calculate where each incoming object will land. If a rocket is going to fall into an empty field, the system simply ignores it ... forgets it.

Think of it like a cricket fielder watching the ball sail comfortably over the boundary rope. No need to dive.

Modern cheap attack drones often use surprisingly simple homing methods, more like smart eyesight than costly military radar. A small camera sends video to a tiny onboard computer trained with thousands of images of tanks, trucks, ships, or radar sets. When the drone spots a match, the software locks on and keeps the target in its cross, adjusting its flight as the object moves, more like a hawk spotting a mouse and diving straight down.

Many drones first fly to a GPS coordinate and then use the camera to identify the exact target. Others follow radio signals or engine heat, a bit like a moth drawn to a bright light.

This simplicity has changed warfare economics. Traditional guided missiles can cost millions. Small AI-guided drones may cost only hundreds or a few thousand dollars. Instead of one expensive weapon, operators can launch swarms. Like bees, each drone is small, but together they can deliver many precise "stings."

Even the Earth has a natural shield—its magnetic field deflects dangerous solar particles. The Iron Dome works in a similar way—detect, predict, intercept.

Because missiles are expensive, scientists are working on a new solution.

Lasers. Yes—real Star Wars-style laser beams.

Israel is developing a system called Iron Beam.

Instead of firing missiles, it fires a high-energy laser that burns through incoming drones.

The advantages are dramatic.

Laser weapons could mean almost zero cost per shot, unlimited ammunition, instant speed.

As long as there is electricity, the laser keeps firing.

It could turn drone defense from expensive fire-works into something closer to switching on a light bulb.

Cheap drones have changed the rules of warfare.

Today's defense systems must be layered, like a security system with many locks.

Future air defense may include—missiles for big threats, guns and drones for smaller threats and lasers for massive swarms.

The goal is simple. Protect cities without bankrupting the defender.

Because in modern warfare, the battle isn't only fought in the sky.

Sometimes it's fought in the balance sheet. ◆

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Scientific Infrastructure in Central Asia: A Comparative Assessment of Innovation Capacity

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Abstract

Scientific infrastructure is widely regarded as a key driver of innovation in emerging and transition economies, yet substantial investments in research facilities often fail to translate into technological and commercial outcomes. This study examines the maturity and effectiveness of scientific infrastructure across five Central Asian economies using a Comparative Infrastructure Maturity Framework (CIMF) that integrates policy analysis, quantitative benchmarking, and expert interviews. The findings reveal a persistent gap between upstream research capability and downstream innovation performance. Even in Kazakhstan—where significant resources have been invested in research institutions and laboratories—the translation of scientific outputs into industrial and commercial applications remains limited. The analysis identifies the underdevelopment of mid–Technology Readiness Level (TRL 4–7) infrastructure as a critical bottleneck, as the absence of testing platforms, pilot facilities, and technology demonstration environments prevents innovations from progressing beyond laboratory proof-of-concept. The study further suggests that scientific infrastructure maturity functions not as a simple linear predictor of innovation success but rather as a threshold condition within innovation ecosystems; without robust mid-stage infrastructure, investments in research capacity rarely produce sustained technological and industrial outcomes. By offering comparative evidence from Central Asia, the paper contributes to a deeper understanding of how infrastructure governance shapes innovation systems and highlights the importance of strengthening technology translation mechanisms in transition economies.

Keywords: scientific infrastructure; innovation systems; technology readiness levels; technology transfer; Central Asia; research infrastructure; innovation policy

1. Introduction

Over the past two decades, Central Asian economies have sought to shift from resource-dependent growth toward more diversified, innovation-driven development. Yet innovation performance remains uneven because research capacity is weakly connected to industrial application—an institutional pattern typical of transition economies where scientific potential exists but innovation systems remain only partially integrated [1,37,38].

Within the National Innovation Systems (NIS) perspective, innovation depends not only on R&D investment but also on interactions among institutions that generate, validate, diffuse, and apply knowledge [2–5]. Scientific infrastructure—including research facilities, metrology systems, testing and certification capacities, and standards platforms—forms a critical foundation for these interactions by enabling experimentation, validation, and diffusion of technologies [5,6]. In emerging economies, infrastructure maturity strongly shapes absorptive capacity and determines whether scientific research can evolve into scalable industrial applications [7,8].

Recent mission-oriented innovation strategies link science and technology investment to societal priorities such as decarbonisation, health resilience, and digital transformation [20–22,43]. Their effectiveness, however, depends on interoperable research infrastructures and coherent governance arrangements [14,18–19]. Where validation environments—particularly at mid Technology Readiness Levels (TRLs 4–7)—are weak, innovation systems experience a persistent “missing middle,” limiting the progression of research toward prototype testing and commercialization [25–27].

Central Asia illustrates these dynamics. Kazakhstan and Uzbekistan have invested in research infrastructure modernisation, while Kyrgyzstan, Tajikistan, and Turkmenistan face deeper structural constraints. Despite divergent reform trajectories, the region shares a Soviet-era scientific legacy and growing policy interest in science-led diversification, making it suitable for comparative analysis [17].

This study develops and applies a Comparative Infrastructure Maturity Framework (CIMF) to examine how scientific infrastructure conditions innovation capacity across five

Central Asian economies. The framework evaluates five pillars—research assets, human capital, governance and standards, research–industry translation mechanisms, and financing instruments—combining policy review, R&D benchmarking, bibliometric and patent indicators, and expert interviews to provide a comparative diagnostic of innovation system performance [13,15].

1.1 Research Gap

Evidence on scientific infrastructure in Central Asia remains fragmented. Existing studies often rely on aggregate indicators that obscure infrastructural constraints [13], lack replicable frameworks for cross-country comparison [14], or emphasise institutional reform while under-specifying mid-TRL translation mechanisms [25–27]. Consequently, policy frequently prioritises upstream research investment while neglecting translational infrastructure and demand-side instruments.

1.2 Research Questions and Hypotheses

This study examines scientific infrastructure as a determinant of innovation capacity across five Central Asian economies and addresses four questions:

- RQ1. How does infrastructure maturity vary across countries, and what upgrading trajectories are observable?
- RQ2. Which infrastructure dimensions most constrain innovation capacity?
- RQ3. To what extent does the absence of mid-TRL infrastructure explain weak research-to-innovation translation?
- RQ4. What are the implications for national upgrading and regional coordination?

Three propositions guide the analysis:

- H1 (Infrastructure maturity): Higher infrastructure maturity is associated with stronger innovation capacity.
- H2 (Missing middle): Underdeveloped mid-TRL infrastructure (TRL 4–7) constitutes the principal constraint on innovation capacity.
- H3 (Governance complementarity): Infrastructure investments generate stronger outcomes when complemented by reforms in standards systems and academia–industry alignment.

Innovation systems evolve through non-linear and path-dependent processes. The framework therefore functions as a diagnostic tool, identifying structural bottlenecks—particularly at mid TRLs (4–7)—that determine whether scientific capacity translates into applied technological outcomes.

2. Conceptual Foundations: Scientific Infrastructure, Innovation Systems, and Technology Translation

Understanding how scientific infrastructure shapes innovation capacity requires integrating innovation systems theory, infrastructure governance, and technology translation mechanisms [2–6]. In emerging and transition economies, innovation performance depends less on R&D expenditure alone than on the coherence of institutions that generate, validate, diffuse, and apply knowledge [1,7,8]. This section outlines the conceptual foundations of the Comparative Infrastructure Maturity Framework (CIMF), emphasising infrastructural maturity as a key determinant of innovation trajectories in transition contexts such as Central Asia [12,34].

2.1 Innovation Systems and Scientific Infrastructure

The National Innovation Systems (NIS) perspective conceptualises innovation as an interactive process among universities, research institutes, firms, intermediaries, and regulators [2–5]. Innovation outcomes therefore depend on the strength of institutional linkages rather than investment levels alone [6]. Within this system, scientific infrastructure—laboratories, testing centres, metrology institutions, shared instrumentation, and data platforms—provides the operational foundation for experimentation, validation, and standardisation [5,14,18].

Scientific infrastructure performs three essential roles. It enables reliable knowledge production through advanced instrumentation [13,15]; supports validation and certification through recognised standards and testing systems [31]; and reduces collaboration costs by providing shared facilities and interoperable research platforms, particularly where firms lack internal R&D capacity [17,38]. In late-industrialising economies, infrastructure maturity therefore shapes firms' absorptive capacity and participation in global value chains [7,8]. Limited access to accredited testing or certification facilities increases technological risk and constrains industrial upgrading, making infrastructural gaps binding constraints on innovation even where research capacity exists [12,31,35].

2.2 The Mid-TRL "Missing Middle"

A major challenge in transition economies is converting scientific outputs into commercially viable technologies [24,25]. Effective translation requires institutional mechanisms—intellectual property systems, technology-transfer offices (TTOs), incubators, and research–industry intermediaries—supported by pilot facilities, testing platforms, and certification infrastructures [23,24,26,27,39].

This study conceptualises translational weakness as a "missing middle" at Technology Readiness Levels (TRLs 4–7) [25–27]. While early-stage research (TRLs 1–3) and late-stage deployment (TRLs 8–9) may exist, mid-TRL development depends on specialised infrastructures such as pilot lines, accredited laboratories, metrology centres, and regulatory sandboxes [28,29,31,35]. These environments enable prototype testing, reduce uncertainty, and facilitate firm participation in technology development.

Mission-oriented innovation strategies—which align research investments with societal priorities such as decarbonisation, health resilience, and digital transformation—further highlight the importance of such infrastructures [20–22,43]. In many transition economies, however, mission programmes emphasise upstream research while underinvesting in mid-TRL validation capacity [25,26]. As a result, innovation pipelines remain incomplete: scientific output grows, but industrial uptake remains limited, reinforcing dependence on imported technologies [7,24,12,38].

2.3 Governance and Financing Complementarities

Scientific infrastructure effectiveness depends not only on physical assets but also on governance capacity and financing structures [30]. Sustainable infrastructures require stable funding, skilled technical personnel, transparent access regimes, and performance-oriented management systems [14,31]. Returns to infrastructure investment increase when complemented by coherent regulatory frameworks, accreditation systems, and evaluation mechanisms [6,30].

In many transition economies, fragmented governance and unstable funding undermine long-term infrastructure utilisation [34,38]. Facilities may exist physically yet remain institutionally immature—underused and weakly integrated into national innovation systems [14]. Demand-side instruments such as innovation procurement, challenge funding, co-financing schemes, and standards-based incentives further shape infrastructure effectiveness by encouraging technology adoption and industry participation [35,43]. Infrastructure maturity therefore reflects a combination of assets, governance arrangements, financing mechanisms, and translation incentives [6,14].

2.4 Relevance to Central Asia and the CIMF

Central Asia illustrates the structural relationship between infrastructure maturity and innovation capacity [12,34]. The region's five economies share Soviet-era scientific legacies but exhibit divergent reform trajectories [38]. Kazakhstan and Uzbekistan have modernised research infrastructures and governance frameworks, while Kyrgyzstan, Tajikistan, and Turkmenistan face deeper constraints related to financing intensity and institutional coordination.

Regional scarcity of high-value infrastructures—accredited laboratories, pilot facilities, and advanced instrumentation—also creates risks of duplication and underutilisation [18,19]. These conditions strengthen the case for cooperative approaches such as a Central Asia Research Commons, enabling shared facilities and harmonised standards [17].

Building on these foundations, the CIMF evaluates five interdependent pillars: (i) research assets, (ii) human capital, (iii) governance and standards, (iv) research–industry translation mechanisms, and (v) financing and demand-pull instruments [6,23,33]. The framework enables systematic comparison across heterogeneous transition systems while identifying mid-TRL bottlenecks that constrain innovation-led growth [25–27].

3. Methodology and Research Design

3.1 Research design and analytical logic

This study employs a comparative mixed-methods design to examine how scientific infrastructure maturity shapes innovation capacity in transition economies, focusing on Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan [6,32,33]. The approach follows the conceptual framework (Figure 1), linking infrastructure maturity to innovation outcomes through translational capacity at mid Technology Readiness Levels (TRLs 4–7) [25–29].

Scientific infrastructure maturity is operationalised through the Comparative Infrastructure Maturity Framework (CIMF), consisting of five interdependent pillars:

- (P1) research assets and instrumentation;
- (P2) human capital and mobility;
- (P3) knowledge governance and standards;
- (P4) research–industry translation mechanisms;
- (P5) financing and demand-pull instruments.

These pillars represent theoretically grounded components influencing innovation performance directly or indirectly [6,32,33].

The CIMF is implemented through a triangulated evidence strategy combining:

i. structured document and policy review;
ii. quantitative benchmarking indicators (R&D, bibliometrics, patents, innovation proxies); and
iii. semi-structured expert interviews.

This design allows cross-country comparison while accounting for institutional heterogeneity and data limitations typical of transition contexts [13,15,34].

3.2 Unit of analysis, scope, and comparative logic

The unit of analysis is the national innovation system of each country [2–5]. The comparative framework identifies both within-country maturity patterns across CIMF pillars and cross-country systemic bottlenecks despite different reform trajectories [32,33]. The region's shared Soviet-era scientific legacy combined with divergent post-independence reforms provides a suitable setting for analysing infrastructure–innovation linkages [12,34,38].

3.3 Operationalisation: from conceptual model to measurable pillars

The methodology distinguishes three analytical layers:

- Infrastructure maturity inputs (CIMF pillars P1–P5)
- Translational capacity as the mediating mechanism (mid-TRL focus)
- Innovation outcomes measured through proxy indicators

This structure separates enabling conditions from outcomes, avoiding circular inference and aligning with innovation systems literature [32,33].

3.3.1 CIMF pillar construction

Each pillar is defined through measurable sub-dimensions and evidence cues:

- P1: laboratories, core facilities, digital platforms, instrumentation, and utilisation [4,18,19];
- P2: researcher base, skills renewal, doctoral pipeline, mobility, and collaboration [7,12,18];
- P3: accreditation, metrology, standards harmonisation, quality assurance, IP and data governance [30,31];
- P4: research–industry linkages, applied institutes, incubators, TTOs, PoC support, and validation capacity [23–27,39,45];
- P5: financing stability, co-funding, innovation procurement, and demand-pull instruments [11,20–22,43].

This structure ensures transparency, theoretical consistency, and replicability [6,32,33].

3.4 The mid-TRL lens: identifying the "missing middle"

A key feature of the methodology is the focus on mid-TRL infrastructure (TRLs 4–7), including pilot facilities, prototype validation, testing, certification, and applied intermediaries [25–29]. These infrastructures connect upstream research with downstream innovation outcomes [26,27]. Accordingly, P4 (translation mechanisms) is treated as the primary transmission channel. Persistent weaknesses at this level indicate structural barriers generating a research-to-innovation gap [25–27,45].

3.5 Data sources and evidence triangulation

The analysis integrates three evidence streams:

- Document and institutional review of policies, strategies, funding programmes, and infrastructure plans [14,43];
- Quantitative indicators covering R&D intensity, bibliometrics, patents, and innovation proxies [13,15];
- Expert interviews with policymakers, research administrators, intermediaries, and academics [23,24].

Triangulation mitigates weaknesses in innovation statistics common in transition contexts.

3.6 Expert interviews: sampling strategy and protocol

3.6.1 Sampling strategy

Expert interviews validate documentary evidence, identify causal mechanisms, and support CIMF scoring where administrative data are incomplete [23,24,39]. Purposive sampling ensured representation across institutional roles relevant to the framework [25–27]. Selection criteria included formal responsibility, domain expertise, and country-specific knowledge across CIMF pillars.

To minimise bias, respondents were drawn from government agencies, universities and research institutes, innovation intermediaries, and industry actors. Limited snowball sampling helped identify additional high-information respondents while maintaining diversity.

3.6.2 Interview protocol

Semi-structured interviews followed a guide aligned with CIMF pillars and mid-TRL translation mechanisms [25–27], covering infrastructure availability (P1), human capital (P2), governance and standards (P3), translation capacity (P4), and financing instruments (P5). Interviews supported explanatory analysis and measurement validation through thematic coding aligned with CIMF dimensions [32,33].

3.7 Scoring framework: CIMF construction and measurement rules

3.7.1 Rationale for structured scoring

CIMF pillar scores were generated through a structured scoring model that converts heterogeneous evidence into comparable maturity assessments [32,33]. The CIMF measures innovation readiness and enabling conditions, rather than output performance [14].

3.7.2 Scoring scale and anchors

Each pillar is scored on a five-point maturity scale ranging from Nascent (1) to Advanced (5) [14,32]. Pillars are further divided into sub-dimensions with explicit anchors and evidence cues (e.g., core laboratory functionality for P1; accreditation systems for P3; PoC funding and pilot facilities for P4), improving cross-country consistency.

3.7.3 Weight logic

To address concerns over arbitrariness, a two-stage weighting approach is used [32,33]:

i. a baseline equal-weight model (20% per pillar); and
ii. a mechanism-informed sensitivity model assigning slightly greater weight to P4 (25–30%), reflecting its central role in the conceptual framework.

Weights are treated as analytical assumptions and tested through sensitivity analysis (Section 3.9) to ensure robustness.

3.7.4 Aggregation

Pillar scores are aggregated using linear additive aggregation:

$$\mathrm{CIMF}_{country} = \sum_{(i=1)}^{5} w_i P_{\_i}$$

This approach is adopted for transparency and interpretability. Additive aggregation is appropriate here because pillars are conceptually interdependent but analytically separable and reflect complementary components of maturity. Pillar scores are aggregated using linear additive aggregation, a transparent and widely used approach in innovation system indices [13,32].

3.8 Integrating quantitative indicators with maturity scoring

Quantitative indicators are used in two complementary ways [13,15]. First, descriptive benchmarking (R&D intensity, publications, patents, collaboration proxies) contextualises national innovation profiles and checks the plausibility of maturity patterns. Second, innovation outcomes serve as validation and interpretive anchors rather than direct inputs (Figure 1). Higher CIMF maturity is expected to correspond with stronger innovation proxies, although strict causal identification is not claimed given innovation system complexity. This separation avoids circular measurement and improves analytical clarity.

3.9 Reliability, robustness, and sensitivity checks

Several safeguards enhance reliability and credibility [32,33].

Inter-rater agreement. Two researchers independently scored CIMF pillars using explicit anchors, followed by structured reconciliation supported by evidence citations. Agreement was assessed using standard metrics (e.g., percent agreement or Cohen's kappa). Areas with weaker agreement—typically governance and translation—prompted refinement of scoring anchors.

Sensitivity analysis. Robustness was tested through:

i. weight sensitivity, comparing equal pillar weights with a mechanism-informed model assigning higher weight to P4; and
ii. score perturbation, varying pillar scores within plausible bounds (±0.5).

Results show only minor rank shifts, while core findings remain stable: Kazakhstan and Uzbekistan demonstrate higher maturity, and mid-TRL infrastructure emerges as the most consistent binding constraint.

Triangulation validity. No pillar score relied on a single evidence source; consistency across at least two types—documents, indicators, and interviews—was required. Divergences are reported as governance or implementation gaps.

3.10 Ethical considerations

Expert interviews followed standard ethical research practice [24]. Participation was voluntary, research objectives were disclosed, and results are presented in aggregated form to minimise institutional sensitivity.

3.11 Limitations and robustness considerations

The CIMF is a structured maturity diagnostic rather than a precise measurement instrument [12,24,32–34]. Interpretive judgement is mitigated through explicit scoring anchors, inter-rater protocols, triangulation, and sensitivity testing. The study does not claim strict causality; infrastructure maturity is treated as an enabling condition, while quantitative indicators serve for benchmarking and plausibility checks.

Cross-country comparisons are limited by uneven data availability, reporting standards, and time lags between infrastructure investments and observable outcomes, particularly in Turkmenistan. Its scores are therefore treated as indicative, and robustness tests excluding this case were conducted. Core conclusions—especially the central role of mid-TRL translation capacity as a regional constraint—remain stable.

Overall robustness is supported by weighting sensitivity, score perturbation, and multi-source triangulation, indicating that observed patterns reflect systemic constraints rather than artefacts of index construction.

4. Results

4.1 Comparative Overview

This section presents empirical findings from the Comparative Infrastructure Maturity Framework (CIMF) assessment across Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan. Results reveal cross-country asymmetry alongside a region-wide bottleneck in mid-stage technology translation (TRLs 4–7) [25–29].

Kazakhstan ranks highest in aggregate maturity, followed by Uzbekistan, reflecting stronger governance reforms, greater fiscal capacity, and structured modernisation of science and higher education systems [14,34]. Kyrgyzstan and Tajikistan display lower maturity due to fragmented institutions, limited R&D intensity, and reliance on external funding. Turkmenistan exhibits selective state-supported capacity but limited system integration, weak international interoperability, and underdeveloped research–industry linkages, constraining innovation impact [34,38].

A key finding is that stronger upstream scientific capacity does not systematically translate into downstream innovation performance. Across all five countries, infrastructures supporting prototyping, pilot validation, industrial testing, and certification remain limited [25–27,31]. This creates a structural “missing middle” in the innovation pipeline: research capacity and policy intent exist, yet technologies rarely progress beyond proof-of-concept due to weak applied testing environments and market-facing intermediaries [23–27,39,45].

Accordingly, the results are presented in two stages. Section 4.2 examines aggregate maturity patterns and anomalies, while Sections 4.3–4.7 analyse pillar-level dynamics (P1–P5), identifying how infrastructure components influence translational capacity and innovation readiness [32,33].

4.2 Aggregate CIMF Results: Patterns and Explanatory Boundaries

Aggregate CIMF scores broadly correlate with innovation capacity proxies, consistent with National Innovation Systems theory, which emphasises institutional coherence rather than R&D expenditure alone [3,4,6]. However, deviations from a simple linear relationship are evident.

The ranking—Kazakhstan highest, followed by Uzbekistan, then Kyrgyzstan and Tajikistan—aligns with differences in research assets and funding. Yet comparisons with innovation proxies such as patenting, industry collaboration, and early commercialisation reveal non-monotonic relationships, consistent with findings from late-industrialising contexts [8,12].

Kazakhstan’s relatively high CIMF score does not translate proportionally into downstream innovation. Despite stronger research assets (P1) and human capital (P2), industrial uptake and certification-linked commercialisation remain modest. This divergence reflects weak absorptive capacity, incomplete translational environments, and governance frictions, which can neutralise upstream strengths [7,8,34]. Infrastructure maturity therefore appears necessary but insufficient for sustained innovation translation.

By contrast, Uzbekistan exhibits sector-specific applied innovation outcomes exceeding expectations based on its mid-range CIMF score. Targeted state programmes and mission-oriented interventions partly compensate for weaker systemic translation infrastructure, a pattern observed in other transition economies [11,20,21]. However, these successes remain episodic and do not eliminate structural pipeline bottlenecks.

These findings suggest a configurational dynamic: countries with similar aggregate maturity can produce different innovation outcomes depending on pillar interactions. Strong upstream capacity (P1–P2) does not yield sustained innovation without mid-TRL environments, while selective downstream initiatives generate limited outputs without systemic strengthening. This pattern aligns with “valley of death” literature, which identifies mid-stage validation as a decisive innovation bottleneck [26,27,45].

The cases of Kyrgyzstan and Tajikistan reinforce this interpretation. Although scoring lower across CIMF pillars, both occasionally generate applied outputs through donor-supported projects or external partnerships.

However, these outcomes remain volatile and non-cumulative due to the absence of institutionalised mid-TRL infrastructure [23,24].

Overall, the aggregate results show that CIMF functions effectively as a diagnostic framework for enabling conditions, but less reliably as a direct predictor of innovation outputs. Infrastructure maturity influences innovation only when aligned with governance structures, translation mechanisms, and absorptive capacity.

This motivates the pillar-level analysis in Sections 4.3–4.7, which examines where infrastructure maturity fails to translate into innovation and where targeted interventions generate limited but fragile successes.

4.2A Mid-TRL Translation Failure in Kazakhstan

Kazakhstan illustrates how mid-TRL infrastructure gaps constrain innovation even in comparatively advanced systems. As the region's highest-ranked country in CIMF maturity, it represents a "most-likely" case: if translation failure occurs here, upstream infrastructure alone cannot explain innovation outcomes.

Over the past decade Kazakhstan has invested heavily in universities, national laboratories, and strategic research programmes, strengthening research assets (P1) and human capital (P2). Yet technologies emerging from these environments frequently encounter bottlenecks beyond early proof-of-concept stages.

Across sectors such as advanced materials, agri-biotechnology, and applied energy, the main constraint is the lack of pilot-scale validation facilities. Research groups can demonstrate laboratory functionality (TRL 2–3) but lack pilot lines, accredited testing environments, and certification pathways required for TRL 5–7 progression. Prototypes therefore stall before industrial uptake or require costly foreign validation.

Existing incubators and technology transfer offices cannot compensate for the absence of physical translation infrastructure such as pilot facilities, metrology services, and conformity assessment systems. Consequently, commercialisation remains episodic and dependent on exceptional arrangements or international partnerships.

Innovation proxies reflect this divergence: despite strong research output and infrastructure investment, patenting intensity and certification-linked commercialisation remain modest relative to upstream capacity. The Kazakhstan case thus supports the study's central argument: mid-TRL infrastructure is a threshold condition for innovation translation.

4.2B Selective Mid-TRL Activation in Uzbekistan

Uzbekistan provides a contrasting case. Despite lower upstream maturity in research assets (P1) and human capital (P2), targeted mission-oriented programmes have partially activated mid-TRL translation pathways.

In sectors such as agri-technology, materials processing, and applied health technologies, specialised applied centres provide pilot testing, field validation, and early certification processes, enabling selected prototypes to reach limited industry uptake.

However, these initiatives operate through narrow, programme-based pathways rather than system-wide infrastructure. Access to pilot facilities is uneven, utilisation varies across sectors, and scaling remains constrained by weak standards harmonisation and certification capacity.

Consequently, Uzbekistan shows applied innovation outcomes somewhat stronger than predicted by its aggregate CIMF score, yet these gains remain fragile and dependent on continued programme support.

Together with Kazakhstan's experience, this case highlights two insights:

i. even partial mid-TRL capacity can enable applied innovation despite moderate upstream maturity; and
ii. without systemic mid-TRL integration, such gains remain non-durable.

A Failed Expectation and Its Implications

Innovation systems theory suggests that stronger research assets (P1) and human capital (P2) should produce stronger downstream innovation outcomes [3,4,6,7,8,25,26]. Kazakhstan, with the highest CIMF maturity, would therefore be expected to outperform regional peers in industrial uptake and commercialisation.

Empirically, this expectation is only partially realised. Kazakhstan's downstream indicators are only modestly stronger than those of countries with lower infrastructure maturity, and in some cases comparable to Uzbekistan.

This divergence indicates that upstream infrastructure accumulation alone cannot explain innovation performance. The absence of operational mid-TRL environments and complementary governance structures can offset the benefits of research investment.

The findings therefore support a configurational interpretation of innovation systems: outcomes depend not on aggregate infrastructure volume but on alignment between research assets, translational mechanisms, and institutional coordination.

4.3 Pillar-Wise Results Roadmap

Following the conceptual framework (Figure 1), results are presented in analytical order [6,32,33]:

- P1: Research assets & instrumentation — infrastructure availability, access regimes, digital platforms, and operational capacity [14,18,19].
- P2: Human capital & mobility — skills pipeline, doctoral training, incentives, and talent flows [7,8,12].
- P3: Knowledge governance & standards — accreditation, metrology, standards alignment, and IP/data governance [30,31].
- P4: Research–industry translation mechanisms — mid-TRL facilities, pilot/testbeds, proof-of-concept support, and intermediaries [23–27,39,45].
- P5: Financing & demand-pull instruments — funding stability, co-financing, procurement, and policy levers [11,20–22,43].

Across pillars, P4 (translation) emerges as the key constraint: even where P1 and P2 are relatively strong, innovation outcomes remain limited without reliable prototype validation, certification, and early commercialisation pathways [25–27].

Table 1. CIMF maturity summary and dominant bottlenecks in Central Asia
(5-point maturity scale: 1 = nascent; 5 = advanced)

Country	Overall CIMF maturity	P1 Research assets	P2 Human capital	P4 Translation (mid-TRL)	Dominant constraint
Kazakhstan	High	High	Medium–High	Medium	Incomplete mid-TRL testbeds and weak commercialization depth
Uzbekistan	Medium–High	Medium–High	Medium	Low–Medium	Mid-TRL infrastructure gaps and limited certification capacity
Kyrgyzstan	Low–Medium	Low–Medium	Low–Medium	Low	Fragmented governance and weak translation intermediaries
Tajikistan	Low	Low	Low–Medium	Low	Underinvestment, talent constraints, missing mid-TRL capacity
Turkmenistan	Low–Medium*	Medium*	Low–Medium	Low	Weak system integration and international interoperability

Notes: Scores reflect operational maturity and ecosystem integration, not merely the presence of isolated infrastructure assets; see Section 3 for scoring rules and triangulation logic.

Key findings:

- National innovation systems show selective strengths but weak systemic integration.
- Mid-TRL translation capacity (P4) is the most consistent constraint limiting returns to upstream research investments.

4.3 P1 — Research Assets and Instrumentation

Key finding: Research asset maturity is uneven. Kazakhstan and Uzbekistan have modernised facilities, while Kyrgyzstan and Tajikistan face capital and utilisation constraints; across all countries, access governance and maintenance remain bottlenecks [14,18,19].

4.3.1 Comparative Results

P1 assesses the availability, quality, accessibility, and operational maturity of research assets [14]. Maturity reflects not only asset presence but also access rules, maintenance systems, technical staffing, and utilisation intensity [31].

Kazakhstan shows the highest maturity due to sustained investment [34], though infrastructure is concentrated in flagship centres, limiting system-wide access [37]. Uzbekistan demonstrates medium-to-high maturity with recent upgrades [34], but renewal cycles and shared-access regimes remain incomplete [14]. Kyrgyzstan and Tajikistan exhibit low-to-medium maturity due to limited equipment depth, maintenance funding, and calibration capacity [31,38], increasing reliance on external testing [35]. Turkmenistan maintains selective assets but limited interoperability and open access, reducing innovation impact [6,34].

4.3.2 Translation Implications

Limited shared labs and calibrated testing environments prevent prototypes from advancing toward certification, reinforcing the regional "missing middle" [25–27,31].

4.4 P2 — Human Capital and Mobility

Key finding: Human capital constraints are structural. Despite relative advantages in Kazakhstan and Uzbekistan, the region faces talent outflows, limited doctoral scale, and weak incentives for applied research [7,8,12,38].

4.4.1 Comparative Results

P2 evaluates researcher scale, renewal, applied-research incentives, and mobility networks [7,8]. Kazakhstan shows the strongest profile due to scale and internationalisation [12], although incentives remain publication-oriented rather than translation-focused [24,29]. Uzbekistan demonstrates medium maturity with ongoing reforms but faces shortages in applied research and innovation-management roles (e.g., TTOs, certification bodies) [7,24]. Kyrgyzstan and Tajikistan remain constrained by small workforces, weak career pathways, and outward mobility [8,38]. Turkmenistan retains training capacity but limited international integration, restricting exposure to frontier standards [34].

4.4.2 Translation Implications

Innovation translation requires engineers, QA specialists, certification experts, and technology managers—not only researchers [23,25]. The regional "missing middle" thus reflects a shortage of these professional roles [26,27].

4.5 P3 — Knowledge Governance and Standards

Key finding: Governance maturity differentiates systems. Weak metrology and certification ecosystems undermine industrial translation even where research capacity exists [30,31].

4.5.1 Comparative Results

P3 measures accreditation systems, standards harmonisation, IP clarity, integrity frameworks, and metrology capacity [30,31]. Kazakhstan performs relatively strongly but lacks comprehensive translation-oriented certification pathways [31]. Uzbekistan shows medium maturity with ongoing reforms, though testing and accreditation systems remain incomplete [31]. Kyrgyzstan and Tajikistan exhibit low maturity, where fragmented governance increases commercialisation friction and reduces investor confidence

[31,38]. Turkmenistan faces interoperability and external validation constraints limiting scalability [34].

4.5.2 Translation Implications

Accredited testing and certification systems are prerequisites for mid-TRL progression; thus P3 enables P4 to function effectively [6,32,33].

4.6 P4 — Research–Industry Translation Mechanisms (Mid-TRL Capacity)

Key finding: Mid-TRL translation capacity is the most binding regional constraint. Limited pilot facilities, testbeds, certification pathways, and intermediaries sustain a structural "missing middle" [25–27,45].

4.6.1 Comparative Results

P4 captures TTO capacity, incubation systems, proof-of-concept support, and pilot/test infrastructure enabling movement from TRL 2–3 to TRL 6–7 [23–27,28,29]. Across all countries, P4 maturity is consistently weaker than P1 and P2 [25–27].

Kazakhstan shows medium maturity: innovation institutions exist but pilot-scale validation and certification capacity remain limited [39,45]. Uzbekistan demonstrates low-to-medium maturity with translation mechanisms lagging behind infrastructure upgrades [25,26]. Kyrgyzstan and Tajikistan face systemic translation gaps due to scarce applied centres and pilot facilities. Turkmenistan also shows weak P4 maturity despite selective assets, reflecting limited intermediaries and standards alignment [34].

4.6.2 Translation Implications

Innovation bottlenecks arise less from insufficient research funding than from missing engineering validation capacity and intermediary institutions [25–27,45]. Without mid-TRL infrastructure, technology pipelines stall and reliance on imported technologies persists.

Country Implications (P4)

- Kazakhstan: Expand national pilot/test networks and incentivise industry participation through vouchers and co-funding [26,45].
- Uzbekistan: Develop TRL 4–7 facilities linked to priority sectors (agri-tech, materials, energy, health) [28,29].
- Kyrgyzstan & Tajikistan: Prioritise shared regional translation platforms rather than duplicating high-cost national infrastructure [26,27].
- Turkmenistan: Strengthen certification systems and professional intermediaries; assets without intermediaries cannot translate [31,34].

4.7 P5 — Financing and Demand-Pull Instruments

Key finding: Financing is necessary but insufficient. Weak demand-pull instruments—procurement, co-financing, and market-formation tools—limit the impact of research funding [11,20–22,43].

4.7.1 Comparative Results

P5 evaluates funding stability, competitive grants, industry co-financing, procurement mechanisms, and adoption incentives [11,20,21]. Kazakhstan demonstrates stronger maturity due to higher resources, though funding remains insufficiently aligned with mid-TRL validation and industry partnerships [21,22]. Uzbekistan shows medium maturity with reform momentum but requires clearer mission-linked financing structures [20]. Kyrgyzstan and Tajikistan face low R&D intensity, unstable funding, and donor dependence [38]. Turkmenistan has selective financing capacity but limited demand-pull mechanisms linking funding to innovation adoption [43].

4.7.2 Translation Implications

Supply-push funding alone cannot close the missing middle. Effective financing must support pilot testing, certification readiness, regulatory compliance, and demand-pull instruments such as procurement incentives [20–22,43].

Country Implications (P5)

- Kazakhstan: Expand translation-focused funding (PoC → pilot → certification) and mission-linked procurement [21,22].
- Uzbekistan: Consolidate instruments into coherent pipeline financing aligned with priority sectors [20].
- Kyrgyzstan & Tajikistan: Secure stable funding for shared infrastructure and translation platforms [38].
- Turkmenistan: Introduce demand-pull instruments linking funding to market adoption and standards compliance [43].

4.8 Cross-Cutting Synthesis

The pillar analysis reveals three structural patterns shaping regional innovation capacity [6,32,33].

Result 1: Infrastructure asymmetry.
Central Asia exhibits uneven maturity rather than uniform underdevelopment. Kazakhstan and Uzbekistan show stronger upstream capacity (P1–P3), while Kyrgyzstan and Tajikistan remain constrained by structural investment and workforce limitations. Turkmenistan combines selective assets with weak ecosystem integration [14,34].

Result 2: Translation capacity (P4) as the binding constraint.
Despite differences in upstream maturity, mid-TRL infrastructure remains weak across all countries, limiting prototype validation and certification [23–27,45].

Result 3: Governance as a system multiplier.
Standards, accreditation, and metrology determine whether research infrastructure can generate market-ready outputs [30,31].

Result 4: Financing effectiveness depends on pipeline continuity.
Funding matters most when it ensures continuity from proof-of-concept to pilot validation and early market adoption [20–22,43].

Overall, the regional constraint is systemic pipeline incompleteness rather than lack of research spending [6,12].

4.9 Limits of the CIMF Framework

The analysis also reveals limits to CIMF's explanatory scope. First, CIMF is not a linear predictor of innovation outcomes: upstream maturity does not guarantee commercialization.

Second, it is less sensitive to episodic translation mechanisms where pilot projects operate without systemic embedding. Third, as a maturity diagnostic it cannot capture short-run dynamics or time-lag effects between infrastructure upgrades and innovation outcomes. Fourth, governance indicators do not fully capture political economy factors such as institutional incentives or implementation constraints.

CIMF should therefore be interpreted as a diagnostic framework identifying structural bottlenecks and complementarities, rather than a deterministic innovation index.

4.10 Dynamic and Temporal Limits

CIMF captures system states rather than trajectories. Innovation transitions are non-linear and path-dependent: upstream capacity (P1–P2) typically precedes translation activation. Observable commercialization often emerges only after mid-TRL infrastructure, governance alignment, and demand-pull instruments mature.

Transition tends to follow three phases:

- Accumulation: investment in assets and skills without downstream impact.
- Activation: operational mid-TRL facilities and governance integration emerge.
- Conversion: integrated pipelines generate scalable innovation outcomes.

CIMF can identify structural readiness but cannot predict the timing or stability of innovation take-off. Its value lies in identifying where systems are unlikely to transition without mid-TRL thresholds and institutional integration.

5. Discussion

5.1 Interpreting the Results Through Innovation Systems Theory

Using the CIMF mixed-methods framework, this study assessed scientific infrastructure maturity and its relationship to innovation capacity across five Central Asian economies. The findings support an innovation-systems interpretation: innovation outcomes depend less on individual policy instruments or research assets than on the coherence of institutional complementarities across the innovation pipeline [2–6].

National Innovation Systems theory emphasises interactions among universities, research institutes, firms, intermediaries, and governance bodies [2–5]. The results show that Central Asian systems remain only partially integrated. Scientific capacity and institutional reforms have expanded, yet weak translation environments limit scalable technological upgrading [6,23,24]. The core constraint is therefore a pipeline deficit rather than an upstream deficit, reflecting insufficient mid-TRL infrastructure and professional intermediaries linking research to industrial adoption [25–27].

5.1A Challenging Infrastructure-Led Policy Logic

These findings challenge a common policy assumption that expanding laboratories, higher education, and R&D funding automatically produces innovation-led growth. Evidence suggests otherwise: countries with stronger upstream maturity do not consistently demonstrate superior commercialization performance. Without mid-TRL translation environments, governance alignment, and demand-pull instruments, upstream investments generate diminishing returns.

5.2 The “Missing Middle” as Structural Constraint

A central contribution of this study is identifying the “missing middle” as a binding constraint in regional innovation systems [25–27,45]. Across all countries, mid-TRL capacity (TRL 4–7) remains systematically weaker than upstream research capability [28,29].

Innovation policy often focuses on research funding or entrepreneurship support, yet the decisive bottleneck lies between these stages: applied validation and de-risking environments that enable technologies to move beyond prototypes. Mid-TRL capacity depends on systemic complementarities among calibrated instrumentation (P1), specialised workforce and incentives (P2), standards and accreditation (P3), and pipeline financing (P5). The missing middle therefore represents a systemic capacity gap rather than a single infrastructure deficit [6,32].

5.2A Transition Pathways and Innovation Foresight

Although CIMF is not a forecasting model, it supports transition-oriented foresight by identifying system configurations where innovation transitions are unlikely under current conditions. Evidence from Kazakhstan illustrates that strong upstream maturity can coexist with weak commercialization when translation and governance complements remain incomplete. CIMF thus distinguishes accumulation, activation, and conversion phases of infrastructure maturity, clarifying plausible transition pathways without assuming linear progress.

5.2B Theoretical Contribution

This study extends innovation systems theory by conceptualising infrastructure maturity as a threshold condition for innovation translation. Upstream research capacity produces applied innovation only when mid-TRL infrastructures—pilot facilities, testing environments, certification pathways, and intermediaries—are operational. CIMF shifts analysis from static capability stocks to pipeline dynamics, showing that systems may accumulate scientific assets yet remain in pre-transition states if translation capacity is incomplete.

5.3 Why Upstream Investment Does Not Automatically Yield Innovation

Two mechanisms explain why laboratory modernisation and R&D spending do not guarantee innovation outcomes.

- First, utilisation and access governance constrain returns. Concentration of infrastructure in flagship institutions without shared-core access reduces system-wide utilisation and industrial linkage [14,18,37]. Weak maintenance regimes further reduce operational maturity.
- Second, weak accreditation and standards ecosystems increase uncertainty for firms. Without credible

validation pathways, firms favour incremental improvements or imported technologies. Infrastructure should therefore be understood not merely as capital stock but as an integrated system of assets, skills, governance, and incentives.

5.4 Regional Implication: Toward a Shared Infrastructure Commons

High-value mid-TRL infrastructures—pilot facilities, accredited laboratories, and advanced testing systems—require economies of scale. For smaller systems such as Kyrgyzstan and Tajikistan, duplicating these nationally is inefficient.

The findings support a **regional coordination model—a Central Asia Research Commons—**treating key translational infrastructures as shared public goods with harmonised access and interoperable standards. Such pooling would enable scale efficiency, standards harmonisation, and stronger cross-border collaboration.

Kazakhstan and Uzbekistan demonstrate partial progress through stronger governance capacity and selective mid-TRL development. However, commercialization remains episodic where translation mechanisms are project-based rather than systemic. Infrastructure produces sustained innovation only when complemented by accreditation, metrology, and pipeline financing (P5) enabling progression from proof-of-concept to deployment.

5.5 Policy Implications: Completing the Innovation Pipeline

The results highlight four complementary priorities:

i. Prioritise mid-TRL infrastructures as mission-critical public goods [25–29]—Develop pilot lines, testbeds, proof-of-concept centres, and accredited validation environments.
ii. Professionalise translation intermediaries [23,24,39]—Strengthen technology transfer offices and applied intermediaries through training, stable funding, and translation-oriented incentives.
iii. Strengthen governance and standards ecosystems [30,31]—Accreditation and metrology institutions define the trust environment for innovation adoption and must be integrated into translation strategies.
iv. Build demand-pull instruments [20–22,43]—Innovation procurement, validation vouchers, co-financing tools, and mission-linked challenge funds can reduce adoption risk and sustain pipeline continuity.

These measures function as complementary components of infrastructure maturity [6,32].

5.6 Implications for Comparative Innovation Research

Beyond Central Asia, this study contributes to comparative innovation scholarship by:

Conceptualising infrastructure maturity as a multidimensional construct integrating physical and institutional elements.

Demonstrating empirically that mid-TRL capacity explains translation gaps in transition economies.

Reinforcing a system-complementarity perspective, where infrastructure generates returns only when embedded in governance, translation mechanisms, and demand-pull instruments.

Evaluation metrics should therefore move beyond upstream indicators such as R&D spending and publications toward translation-throughput measures, including prototype-to-certification progression and testbed utilisation.

6. Conclusion

This study developed and applied a Comparative Infrastructure Maturity Framework (CIMF) to assess scientific infrastructure maturity and innovation capacity across Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan. Using a comparative mixed-methods approach—combining policy and institutional review, quantitative benchmarking indicators, and expert interviews—the study provides one of the first structured regional diagnostics of the infrastructural foundations of innovation systems in Central Asia [6,12].

6.1 Summary of Key Findings

Four conclusions emerge.

- First, Central Asia's innovation landscape reflects asymmetric infrastructure maturity rather than uniform underdevelopment. Kazakhstan and Uzbekistan demonstrate stronger progress in upstream pillars—research assets (P1), human capital (P2), and governance reforms (P3)—while Kyrgyzstan and Tajikistan remain constrained by limited investment, fragmented institutions, and sustained talent outflows. Turkmenistan exhibits selective strengths but limited system integration and international interoperability.
- Second, the most consistent regional constraint is weak research–industry translation capacity (P4), confirming the "missing middle" proposition. Underdeveloped mid-TRL infrastructure (TRL 4–7)—including pilot facilities, testbeds, accredited validation environments, and certification-linked testing—limits the conversion of scientific outputs into scalable technologies.
- Third, knowledge governance and standards (P3) emerge as a critical enabling pillar. Accreditation, metrology, and standards ecosystems determine whether research infrastructure can operate at scale and whether prototypes can progress toward market adoption.
- Fourth, financing (P5) is most effective when structured to sustain continuity across the innovation pipeline and supported by demand-pull instruments. Supply-driven research funding alone cannot resolve translation bottlenecks unless it also supports prototype de-risking, compliance testing, early market formation, and industry collaboration.

6.2 Contributions

The study contributes to innovation systems research and policy in transition economies by:

- proposing a replicable framework for assessing infrastructure maturity as an integrated system

combining assets, skills, governance, translation intermediaries, and financing instruments;
- providing comparative empirical evidence on Central Asia, clarifying why upstream improvements do not automatically generate innovation outcomes;
- identifying mid-TRL infrastructure as the most consistent system bottleneck linking scientific capability to innovation performance.

6.3 Limitations

Several limitations should be noted. Innovation systems are multi-causal, and while CIMF clarifies structural mechanisms, the analysis does not claim strict causal identification. Cross-country indicators may reflect reporting inconsistencies and time-lag effects between infrastructure investment and observable commercialization outcomes. Although triangulation and inter-rater scoring reduce subjectivity, maturity assessment inevitably involves interpretive judgement. Expert interviews strengthen explanatory depth but may underrepresent private-sector perspectives where innovation activity is informal or poorly documented.

6.4 Future Research

Future research could strengthen causal inference and measurement precision by:

i. developing longitudinal datasets on infrastructure utilisation and maintenance cycles;
ii. integrating firm-level innovation surveys and project pipeline data; and
iii. testing CIMF results against direct translation indicators such as prototype-to-certification rates, pilot facility utilisation, and licensing volumes.

Comparative studies across other transition regions would further test the generalisability of the mid-TRL “missing middle” mechanism and refine infrastructure maturity theory.

6.5 Closing Statement

Overall, the findings indicate that Central Asia’s innovation constraint is fundamentally systemic. Progress depends on completing the research-to-innovation pipeline through mid-TRL infrastructure, professional intermediaries, stronger governance and standards ecosystems, and demand-pull instruments enabling technologies to reach adoption and scale. The CIMF framework offers a structured basis for guiding such reforms through evidence-based prioritisation and cross-country learning.

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