TRG during his recent illness was exemplary and heart-warming.

I visited the family a few days ago to express my condolences. Rajagopalan was kind enough to show me one of TRG's bequests, his orchid collections, Dendrobiums, Vandas and a few other species. Some were on the ground, while about a thousand were in the climate-controlled terrace. He told me that he would try to preserve this inheritance for which he had trained himself. Natural products chemistry is another bequest of TRG which needs to be preserved and pursued. N. S. Narasimhan at Poona University practised it very ably for several years. I have retained a significant interest in the area, but circumstances took me into synthetic medicinal chemistry. Now the country looks to young, gifted organic chemists to carry on the work of TRG.

K. NAGARAJAN

Hikal R&D Centre,
Bannerghatta Road,
Bangalore 560 076, India
e-mail: n_kuppuswamy@hotmail.com

Satish Dhawan

Satish Dhawan, former Director of the Indian Institute of Science (IISc) and Chairman of the Space Commission, and President of the Indian Academy of Sciences during 1977–1979, passed away on the night of 3 January. Although he had been growing physically infirm during the previous half-year, he had remained his usual cheerful self till the very end, and died peacefully within twenty minutes of complaining about difficulty in breathing. With his death the country lost one of its most distinguished sons, and the scientific community a truly unimpeachable representative. He had at various times in his career been teacher, research scientist, engineer, technologist, manager, leader and adviser – sometimes many of these at the same time. And to everything he did he brought dedication, breadth of vision, meticulousness and humanity, which, combined with his remarkable scientific and technological abilities, transformed every organization he worked for or led, and made it achieve what it had often not thought itself capable of.

Satish Dhawan was born on 25 September 1920 in Srinagar, and was educated in this country and the United States. He graduated from the University of Punjab (Lahore) with an unusual combination of degrees: a BA in Mathematics and Physics, an MA in English Literature, and a BE in Mechanical Engineering. In 1947 he obtained an MS in Aeronautical Engineering from the University of Minnesota, and moved to the California Institute of Technology (Caltech), where he was awarded the Aeronautical Engineer's Degree in 1949 and a PhD in Aeronautics and Mathematics in 1951 with the eminent aerospace scientist and fluid dynamicist Hans W. Liepmann (Honorary Fellow of the Indian Academy of Sciences) as adviser. This educational breadth, covering science, engineering and the humanities, and his distinguished family background, appear to have given Dhawan an ability to view the world from many different angles, and may explain in part his unique qualities as a leader.

Dhawan had spent a year on the shop floors of Hindustan Aircraft (now Hindustan Aeronautics, HAL) before leaving for the US on a government scholarship. As a student at Caltech he made an extraordinary impression, and left a glow of fond memories behind him when he left to return home in 1951 – for here was an Indian who was not only ingenious at hooking up new and intriguing experiments but could also play with hypergeometric functions, quote Shakespeare for every occasion, and regale his friends with stories about the camel answering to the name of Greta Garbo in the Khyber Pass (Dhawan grew up as a young man in what is now Pakistan). The charm of his personality overwhelmed everybody that came to know him, especially as it was accompanied by a very Indian sense of grace and modesty.

At the time that Dhawan began his career in aerodynamic research, supersonic flows and shock waves were still rather exotic phenomena; his earliest papers dealt with these subjects, and one of them, which had detailed observations of how a shock wave bounces off a solid surface (such as that of a wing, for example) became widely known for its revealing and defining observations. For his PhD thesis he

Dhawan laughing away with young scientists at the First Asian Congress of Fluid Mechanics, Bangalore, 1980.

invented an ingenious method of directly measuring the friction drag on a surface by letting a small strip of it – about a millimeter wide – float, and measuring its effective deflection against the resistance of a spring by electronic methods, using a null technique[1]. These results appeared in various books of the time, including the first edition of the English translation (from German, published in 1955) of Schlichting's book *Boundary Layer Theory,* the first on the subject. They have been faithfully reproduced in the many editions the book has gone through over the last fifty years, including the eighth published in 1999 (ref. 2).

At IISc, which he joined as a Senior Scientific Officer in 1951 (he became Professor and Head of the Department of Aeronautical Engineering in 1955, and Director in 1962), he built the first supersonic tunnels in the country. (The very first was a tiny tunnel with a test section of 1 cm × 1 cm or so, running on compressed air stored in two war-surplus oxygen tanks from a Dakota.) I first met him when I joined the Institute as a student in 1953. That is now nearly fifty years ago, but my recollections of early encounters with him are still vivid. I recall a tall, handsome, young man who would jump out of his sporty little MG car, wearing a red shirt and a broad smile, racing across the stair-case in the Department and cheerfully saying 'Good morning' as he stepped into the class room. Dhawan brought to the Institute an element of youth, freshness, modernity, earnestness and Californian informality that captivated the students and many colleagues. In short, he was a star on the campus.

Students liked his classes very much indeed, and for a variety of reasons; the first of these was, as I have already remarked, Dhawan's general cheerfulness in his approach to the subject as well as to the students. He took his teaching very seriously, and supplied his classes with plenty of notes, data sheets, diagrams and so on. He worked hard on all these – one would often see him in his office late at night – and he expected the students to work just as hard – which many of them cheerfully did. Another reason for the great popularity of his classes – last but not least, as they say! – was that he was generous with his grades if the student had got the gist of what had been taught in the classroom.

To anyone who walked into the laboratory that he set up at the Institute, one thing that caught immediate attention was that every thing looked different, and worked well. The laboratory managed to convey an impression of both science and engineering; it had 100 hp compressors running wind tunnels, as well as lenses and galvanometers measuring what was going on in those tunnels. In a very real sense I think Dhawan established, at IISc and – by example – elsewhere in the country, a tradition of scientific research on engineering problems. His laboratory also had a variety of little devices, rigged up by him with great and obvious pleasure, to make things a bit easier for the experimenter. Among these 'gizmos', as he loved to call them, I remember a pretty little thing for electroplating 5 micron tungsten wires with copper, so that they could later be soldered for making hot wire probes – I started my life in the laboratory, like so many students of fluid dynamics everywhere in the world at that time, struggling to make these fragile probes for wind tunnel measurements of fluctuating velocities in turbulent flows. I still recall Dhawan teaching me to make these probes, telling me about the ritual one had to follow – 'like doing pooja', he would say. The fine wires we needed for these probes were not easily available, and Dhawan had obtained from his friends in the United States various bits of platinum and tungsten wire which came stuck on the back of letters written to him: we used to hoard them like misers.

I vividly recall how the 1 inch × 3 inch wind tunnel in the High Speed Aerodynamics Laboratory was calibrated, with the help of all hands that could be mustered at any given time, to open valves, ring bells, take readings, click cameras, etc.: it was all very dramatic to me at the time. (Not that the number of people so mustered was very large: the Department was still small then.) He also led a pilot project for the huge facilities that later came up at the National Aeronautical Laboratory (now the National Aerospace Laboratories, NAL) in Bangalore. The students and colleagues he worked with at IISc went on to establish and run the National Trisonic Aerodynamic Facility at NAL – a facility that now may well be the most well-equipped blowdown tunnel in the world. Simultaneously his research in fluid dynamics continued: he and his students made pioneering investigations in the intriguing phenomenon of boundary layer transition, as the flow goes from a smooth, laminar state to the more common eddying, irregular, turbulent state; they also studied reverse transition or relaminiarization, as the flow (under certain conditions) reverts (to everybody's amazement at the time) to the laminar state. Also studied were wall jets, axisymmetric bodies, three-dimensional boundary layers, base flows, separation bubbles, transonic flows and so on. It was almost as if Dhawan wanted to set up a base from which any worthwhile or important topic in aeronautical fluid dynamics could or would be studied.

He was the father of experimental fluid dynamics research in India, and indeed was in many ways the first engineering scientist of the country.

He summarized all of this research in a lecture which he gave at the First Asian Congress of Fluid Mechanics, held in Bangalore during 8–13 December 1980 (ref. 3). And these Asian Congresses, growing stronger with each meeting, were again something that would not have prospered without his moral and material support.

There were two outstanding features of Dhawan's philosophy in research. First, it was carried out at low cost, with ingenious development or adaptation of whatever materials, skills and instrumentation were available at the time; second, the basic research areas investigated in his laboratories were all inspired in some way by the problems faced by the newly-born aircraft industry of the country (which he had known from the year he had spent on the workshop floors before he went to the US). In later years he constantly sought to promote the development of this industry at the higher levels of policy and management, and persuaded HAL to start a division for space projects.

In 1972 Dhawan was appointed Chairman of the Space Commission and of the Indian Space Research Organization (ISRO), and Secretary to the Government of India in the Department of Space. It was an inspired appointment. The Indian space programme owes its birth to the vision of Vikram Sarabhai, but the superb technology development organization it has now become was Dhawan's loving creation. In the decade following his appointment he directed the Indian space programme through a period of extraordinary growth and spectacular achievement. Major projects were carefully defined and systematically executed, including in particular the launch of Indian satellites on Indian rocket vehicles. Pioneering experiments were carried out in rural education, remote sensing and satellite communications, and led to operational systems like INSAT that became (and continue to be) a part of Indian life. These projects were all distinguished by their keen sensitivity to the true needs of a developing nation, a confident appreciation of the ability of its scientists and engineers, and the carefully planned involvement of Indian industry, both public and private. It is no surprise that the Indian space programme has come to be seen in the last two decades as a model of technology development and application carried out within the country. Kalam recalls a late evening in Cauvery Bhavan in Bangalore (where ISRO Headquarters were located at the time) with Dhawan, discussing space missions for the next two decades. While many mission options were debated with all the ISRO engineers that had gathered, Dhawan summarized the next morning his plans with graphs prepared in his own hand, bringing out a space mission profile for the next 15 years (1980–1995). These charts, reproduced in a volume dedicated to him[4], became the blueprints for the national space programme, as it grew into a stable of various launch vehicles (including in particular those for polar and geostationary satellites, PSLV and GSLV), the Indian Remote Sensing satellites, the INSAT series, and their current technological descendants.

The principles that Dhawan formulated and applied (but, characteristically, never stated) in running the country's space programme can be easily inferred from the way he operated. First of all he devised a programme that was societally conscious, with objectives that could be widely understood (weather, natural resource-mapping, communications, etc.). He had supreme confidence in the ability of Indian engineers and scientists, even when they did not have degrees from IITs or foreign universities. He kept the technology development work open and transparent to the national scientific community through an elaborate system of reviews (some of them held in the big auditorium in the Vikram Sarabhai Space Centre at Trivandrum, filled to capacity on such occasions; the tradition was quickly established here that the juniormost engineer could ask awkward questions of the big project leaders). He managed his projects through a small group of very able directors, and another small group of bright young whizkids in his office (protecting them from the natural dislike of their colleagues). He took the responsibility when there were failures, but let others take credit when there were successes (as Kalam has pointed out). He maintained accountability through peer pressure, but shielded his engineers from blame for honest failures. He developed a promotion and assessment system that had some unique features, enabling the more productive engineers to move ahead of their colleagues but not too rapidly, retaining the confidence of the bulk of the staff in the fairness of the system. And he insisted, successfully, that the national space programme should be a purely civilian enterprise.

And there were some other unusual things about his management style. He shunned publicity, and rarely held forth before the media – so much so that people were often surprised how forceful he could be in private, or within the four walls of Council or Commission.

I think of him as a critical optimist in everything he did.

While running the country's space programme he took only one rupee for doing the job, preferring to be paid by IISc for directing it. (When he was asked by Indira Gandhi to take over ISRO as successor to Sarabhai, he made it clear that he would do so only if he could remain at the Institute that he so loved. And when Morarji Desai took over from Indira Gandhi after she lost the elections in 1977, Dhawan was ready with his resignation from ISRO – but Morarji refused to accept it.)

After his retirement from formal positions in Government, Dhawan continued as a member of the Space Commission, after having already become the Bhishma – the doyen – of the Indian aerospace community. He took time every now and then to analyse matters of public policy in science and technology, and kept egging his colleagues in the scientific community to give more attention to the social demands on science.

While doing all the high technology and big science at ISRO, he never forgot how crucially important 'little' science was, and ceaselessly promoted it, especially with young people. Indeed, he indulged in it himself whenever he could; the only book he wrote (to my knowledge) is a little gem on *Bird Flight*[5], which grew out of a lecture he gave first at the Academy, and then at many other places across the country (especially, by his insistence, at those off the beaten track, like Jammu and Guwahati). I still remember how he took a busy break from running his space empire to work on the Academy lecture, drawing his own diagrams and doing his own sums.

During the 19 years that he was Director of the Institute (beginning in 1962), he retained his interest in fluid dynamics and aeronautics, e.g. carrying out an elaborate evaluation of the airworthiness of the HS-748 ('Avro') aircraft flying for Indian Airlines, pioneering a kind of civil aviation research unmatched then or since. (As he had to run both IISc and ISRO at the time, most of the meetings he held – with the small group of some ten scientists from IISc, NAL and HAL that were assisting him – took place late at night.) He devoted much time to the establishment of many new scientific programmes in the Institute, in such areas as automation and control theory, materials science, molecular biology and biophysics, technology for rural areas, theoretical physics, applied mathematics, solid state chemistry and atmospheric sciences. He persuaded such distinguished scientists as G. N. Ramachandran, C. N. R. Rao and George Sudarshan to join the Institute; and he also persuaded a rather reluctant faculty to reform their educational programme. Indeed, his long tenure at the Institute – a record – transformed it from a rather laid-back campus (with strong traditions in only a few areas like physics), to one humming with new ideas in a wide variety of subjects, from fresh young faculty and a great many new students. At the same time he played a key role in formulating the science and technology policy of the country, through such bodies as the Scientific Advisory Committee to the Cabinet. He also helped mould other organizations whose Councils he headed. Most notable among these were the Raman Research Institute and NAL. As Director of NAL during 1984-93, I must place on record how much we benefited not only from his advice and friendly criticism, but much more importantly from his gentle but unceasing pressure on us to promote civil aviation. Dhawan's encouragement, and the enthusiasm of the late Raj Mahindra, provided the inspiration for the civil aircraft projects that NAL went ahead to pioneer.

But what specially distinguished Dhawan from many other eminent scientists and engineers were his extraordinary qualities as a leader and a human being, his great personal charm, and his keen social conscience. When the Sriharikota Range was being built, he rejected a proposal to fence the range to keep cattle from it, noting that the range had belonged to the cattle and the tribals living there, and making alternative arrangements. He set up a museum housing the artifacts that were found at the site. The mechanics making his pet gizmos for him in the Institute laboratories – some of them highly skilled but hardly educated – felt they were his friends, even as the students and his own class-fellows in India and abroad did. He could be, and was, a tough man many times, but never on personal considerations.

If he sometimes seemed indecisive, that was because he accommodated so many diverse points of view within himself; after knowing him for some time I felt I could recognize the churning that went on in his mind on those critical occasions as he balanced, in his own very rational way, all those competing ideas and forces; and he often shared these thoughts with his close colleagues before he made his decisions.

Although he generally gave the impression that he was not particularly interested in Indian philosophy or religion, he once asked me whether there was some brief account I could recommend to him. In spite of this apparent lack of interest, however, he was actually more deeply Indian in his fundamental attitudes and his value system than most philosophy-lovers: he was a true *karma-yōgi*.

Dhawan was honoured widely for his contributions to science and technology by various bodies within India and abroad. When he was invited to deliver the Commonwealth Lecture at the Royal Aeronautical Society[6], he characteristically made a comprehensive review of everything that was being done in the many different aeronautical institutions in the country. He was elected President of the Indian Academy of Sciences in 1977, and awarded the Padma Vibhushan in 1981. He was one of the very few Indians to be elected to the US National Academy of Engineering. He was a Distinguished Alumnus of both Caltech and IISc. Two volumes of scientific papers[4,7] have been published as tributes to him, with contributions from friends and admirers all over the world. Among his numerous other awards, one that deserves particular mention is the Indira Gandhi Award for National Integration, bestowed on him in 1999 with a citation that read in part:

> The award goes fittingly to one of our foremost scientists, teachers, and national builders, Prof. Satish Dhawan, who has made multi-dimensional contributions to scientific education, research, policy formulation and implementation and is deeply concerned with the solution of national problems through the use of science.

He was, most of all, the undeclared but widely accepted moral and social conscience of the scientific community. He was a great man.

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RODDAM NARASIMHA

National Institute of Advanced Studies, Bangalore 560 012; and
Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore 560 064, India
e-mail: roddam@caos.iisc.ernet.in