MY LIFE WORKING WITH LIQUID CRYSTALS
—AND HOW THEY WORK FOR US

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When I first learned that I was to be recipient of the 1995 Kyoto Prize Laureate in Advanced Technology, I quite naturally experienced a number of strong emotional reactions—great pleasure, a deep sense of the honor being done to me, and pride that my peers in Japan which is such a technologically advanced country should have decided that my achievements in science and technology merited such recognition.

Later, I must admit, I began to think “am I really worthy of such a prestigious award and such a high honor?”—for like all scientists I have developed a critical mind which leads me frequently to criticise myself, as well as others. As a result of such personal criticism and self-inspection, I am all too aware of the errors of judgment and decision that have punctuated my career, and this makes me a rather unassuming person, a quality which I find is shared by most people of real quality.

However, as matters developed and I was made more fully aware of the conditions and requirements of the Kyoto Prize Laureates and read Mr. Inamori's own statement about how the awards were conceived and the philosophy behind them, I in fact took comfort, for amongst the criteria relating to the achievements and qualities required of the Laureates, there is one which stresses that the Laureates should be people who are-and I quote “sensitive to their own human fallibility.”

This then led me to think along the following lines—why indeed do I stand here as recipient of this great award and not you, or you, or you in the audience. Is this entirely due to me, did someone up there decide that this should be so, or was an element of luck involved? And the conclusion I reached was that I am not so very different to any of you listening now to what I have to say, and that much of what led to the successful science that I have done was concerned with elements such as where I was born and educated, what I was taught, the infrastructure in which I grew up and lived and the people who impacted on my life. Additionally however, there has been the element of luck concerning the timeliness of what I did in my early research. So I stand here with great pride as a Kyoto Prize Laureate, but with no trace of arrogance or superiority, for I truly believe that, and here I take a saying we have in England—"there but for the grace of God go I"— and change it to "here might any of you stand today, given the training, the opportunities and the good fortune that I have had," coupled of course to the hard work that I have always been prepared to give.

And so I decided that in this Commemorative Lecture I would try to tell you something of my life and the factors that have influenced it. In doing so, I will have to introduce and use some technical and scientific matters, but I will bear in mind that this lecture should not be too technical in nature as so many of you here today are non-scientists. However, it is no more possible for a scientist to describe his life's work and what he has achieved without some scientific input, any more than it would be possible for a poet to do the same without some poetical quotations. And I believe that it is possible for scientists to put across to lay people the essence of their science without losing the listeners' comprehension. Indeed, scientists must become more aware of the importance of communicating their science and scientific matters in general to non-scientists in a way that they can understand, and there is now in the UK a publication of the Royal Society called "Science and Public Affairs" which tries to do this. Indeed, scientists have themselves to blame if they are mistrusted, maligned and not understood, because they have been so bad in the past at communicating what motivates them and what they do. Too few of us take the trouble to use public lectures, the radio and television to explain the benefits that have come to mankind through science, and to emphasise that life in the dark ages was not pleasant and that is where society would be if it were not for the improvements society has gained from scientific developments. As a result scientists are so often blamed for many things without logical thought and understanding by those who lay blame at their feet. Some bad aspects have certainly arisen from scientific activities, but should we, for example, blame the scientists of years ago who invented explosives, because they can be made into bullets and bombs, or do we praise them for the fact that without explosives the dams and reservoirs needed to provide mankind's water supplies could never have been constructed? Should we blame the discoverers of fluorocarbons because of their possible connection with the ozone layer problem, or do we thank them for the relief some such materials have given to mankind in the form of anaesthetics? Should we blame the discoverers of nuclear fission because of atom bombs, or praise them for the cheap energy source so provided? Often the problem stems from how commerce and the military use scientific discoveries, and that is often the consequence of the failure of the users to understand the scientific aspects and the possible consequences stemming from the systems they are handling.

As Mr. lnamori has so wisely said, there is a positive and a negative side to everything—the yin and the yang, the light and the dark. As he says, there is a need for an awareness of both sides of this duality and this can only come from scientific communication between scientists and non-scientists. There could even be a dark side to Liquid Crystals and their relationship to information dissemination-future liquid crystal displays could be involved in the spread of pornographic material for example. But I hope that I do not stand condemned for my part in the science behind these displays. The key to most things lies in education and the ability of different groups of people to understand each other and to inter-relate.

To take this point further, a well-known politician in England—Shirley Williams—once described the problems which lead to the separation of the well paid professional class from the out of work, the homeless and the poor, with the blue collar workers occupying the intermediate region. The analogy she used was an hour-glass—with the well paid in the top compartment and the poor in the lower compartment, the narrow constriction being occupied by the blue collar group. Like the free flowing sand, it is easy to fall from the top compartment, through the constriction, into the lower part if you fail to adapt, and to keep abreast of new trends, new technology and new methodology, and it is impossible to climb out of the lower compartment, through the constriction and into the upper compartment without education and training and its provision of the skills and knowledge necessary to function at the upper level. Education and communication provide the answer to such class separations.

So where did I begin? If you look at a map of the United Kingdom, up there in the lowlands in the South of Scotland, there is a little dot in Stirlingshire which represents the small town of Denny where I spent my life till I went to University in 1943. I was however born in the capital city Edinburgh, but only because apparently I caused my mother problems from the moment I was conceived, and she had to go into hospital to have me delivered. I attended school in Denny however and then went on to study at the University of Glasgow, an ancient University founded in the mid 15th Century. Typically of the Scottish Education system, I was given a very sound education. Scotland, like the other Celtic parts (Ireland and Wales) of the UK is a country where education is properly valued-much more so I fear than in England. As a boy, I was greatly influenced by my father, who was a pharmacist with his own business. In those days, pharmacists compounded their own medicines and often functioned as doctors in emergencies such as accidents. He was educated in Chemistry, Physics and Pharmacy, and he would allow me to help in his dispensary in weighing materials and making pills, powders and solutions. In this way, he introduced me to science, and on Sunday walks he would talk to me about plants, how they grew, the medicinal components they contained and the chemistry of living processes, instilling into me that human beings too are really complex chemical factories, and that we only grow and flourish if our chemistry and physics are right and functioning properly. I was lucky to have such a father, and as a result, from the age of about 11, I never wanted to be anything other than a scientist, and a chemist at that. From that age, I knew about the atoms and molecules which constituted me and all the living and inanimate matter around me. Regrettably today, more than 50 years on, I still find many adults who know nothing of such things and to whom the word molecule is something connected with the mysteries of science. To me, I am afraid, it is an even greater mystery how such people can go through life regarding themselves and the matter around them as just so much "stuff" of different kinds.

At University, I studied Chemistry, with subsidiary Mathematics and Physics. I graduated in 1946, and two aspects of luck entered the picture, one bad and one good. The bad fortune was that my father became seriously ill and could no longer afford to support me through a research degree. I was not therefore a privileged person—I had to find work! The good luck then arose. Purely by chance. I met my Inorganic Professor, Monteith Robertson, the famous X-Ray crystallographer, in the corridor of the department during one of my last few days there and he told me that I could have a temporary position at the University College of Hull where a friend of his was going as the new Professor of Chemistry—he was later to be Sir Brynmor Jones and become Vice-Chancellor of the University. I decided to take this position as University Demonstrator and to turn down an offer to work with the Anglo-Iranian Oil Company in Persia. This lucky event led me not only to the University of Hull where I stayed on, taught and researched for over 40 years and ended up as Professor of Chemistry and Head of Department, but also to an introduction to Liquid Crystals. After a year during which I apparently performed well, I was made Assistant Lecturer, and Professor Jones pointed out that as a member of staff I could do research in my free time for a Doctoral degree. He offered me two subjects-one in the field of reaction kinetics, which did not appeal to me, and one in the more speculative field of liquid crystals in which he had done some work before the war. And so I began to learn about and work with liquid crystals, eventually obtaining my Doctorate of the University of London in 1953 for a thesis entitled “The Mesomorphism of Aromatic Carboxylic Acids.” Therefore you see that some of the reasons why I stand here today as Advanced Technology Laureate in the field of Liquid Crystals are very much bound up with luck and chance meetings and happenings.

Now we should come to the small injection of technology by going back to our molecules which consist of groups of atoms chemically bonded together—holding hands if you like—and forming a coherent molecule. In the case of Liquid Crystal (LC) materials, the best known examples consist of molecules which are moderately stiff and elongated—like a rod or a pen. Most liquid crystals are organic compounds—not organic in the ill-educated sense of the Green Lobby—but properly defined as compounds of carbon, consisting mainly of carbon atoms together with hydrogen atoms and some atoms of oxygen and nitrogen. In a solid crystal such molecules are tightly packed together in a 3-dimensionally organised crystal lattice with very little ability for movement, until the crystal is heated to a particular temperature at which the molecules can no longer hold position in the face of increasing thermal vibrations and the whole system collapses to give a disordered liquid. The crystal has melted (e. g. ice to water, a common example from the area of inorganic chemistry) and order has been destroyed.

If however the crystal consists of rod-shaped molecules, heat first induces rotational motion around the long axes of the rods and they become able slide in the direction of their long axes. The order of the crystal has been lost, but parallel order still remains. We do not have disorder. We have a liquid crystal, partly ordered and partly fluid. This type of LC is the simplest and least ordered kind and is called a Nematic LC. It is this kind which is used in all commercial LC displays that we see today in watches, calculators, lap top PCs, small TV sets etc.

Only when the Nematic LC is heated to a higher temperature does it become fully disordered. Therefore, for particular compounds consisting of rod-shaped molecules, and very many are now known, the Nematic LC state exists over a range of temperature between the stable crystal state and the truly liquid state. As we shall see later, in a small number of interesting cases, the Nematic state can be the stable state at room temperature. Only on freezing does the crystal state form.

Why then is this Nematic state interesting and useful? Well, if we make a thin film of Nematic LC between 2 surfaces, it can be arranged that the parallel molecules lie down flat to the surfaces or, under other circumstances, it can be arranged that they all stand up at right angles to the surfaces. Looking down then on our film, we are either looking down on parallel rods or at the ends of parallel rods. Such a film has different properties in different directions—in particular with respect to light incident upon the film—especially plane polarised light, which is light whose waves are vibrating in only one plane. Such light is produced by passing ordinary light through a sheet of polariser.

This can easily be demonstrated. The light coming from this overhead projector is propagating upwards but the light waves are vibrating in all directions at right angles to the propagation path. This piece of polariser cuts out all the light other than that vibrating in the vibration direction of the polariser material. This is shown by putting another sheet of polariser on top, with its vibration direction parallel to the first. The light still comes through. However, if we rotate the top sheet through 90°, when its vibration direction is then at right angles to the first, all the light is cut off. The polarisers are said to be crossed.

Returning to our thin film of Nematic LC, you must remember that it is fluid—you must have noticed this if you press on your PC screen. It is therefore possible to use an electric field applied across the film to change the orientation of the molecules and thereby the optical properties of the film. For example, with molecules parallel to the surfaces, and using suitably aligned crossed polarisers, it is possible to switch the film from bright to dark (molecules now at right angles to the surfaces). On removing the electric field, the molecules relax back. Consequently, parts only of the display can be addressed electrically by using patterned electrodes, and in this way, numbers, letters, dots and information in general can be portrayed. This is the simplistic basis of the LC Electro-optical Display. In this form however, the device does not give adequate contrast.

Now we come to the elements of luck and timeliness, and the story must develop in two parts.

(1) In 1971-73, 2 separate groups of workers in America and Europe patented

the idea that you could make a thin film of a Nematic LC with a surface induced quarter twist or helix. This is done by arranging the long molecules flat to the glass plates at each surface, but pointing in directions at 90° to each other. The film being fluid, the molecules gradually change their orientation through 90°on passing through the thickness of the film. If we place such a Twisted Nematic film between 2 sheets of polariser with their vibration directions crossed and suitably aligned with respect to the LC molecules, light can still pass through the cell as the plane of polarisation of the light has been rotated through 90° by the quarter helix of the LC. Now by using an electric field (applied using transparent electrodes), the quarter helix can be changed into an alignment with the molecules at right angles to the surfaces. The film no longer rotates the plane of polarisation of the light and the cell will be black. The cell can then be switched from bright to black, and on removing the field, it will relax back to bright again. We have therefore an elegant device which can function as a shutter, or again by addressing only parts of the cell electrically, a display for presenting patterns, numbers, figures or dot matrix formatted information.

(2) The problem was that room temperature LC materials capable of use in such a Twisted Nematic (TN) Display did not exist and the commercial viability of the device could not be realised. In this second part of the story, we come to me and my then very small research group working in Hull on materials of potential use in electro-optic displays. When we became aware of the Twisted Nematic device, we quickly saw a way to solve the materials problem. We would eliminate the central molecular unit used in all earlier materials to lengthen the molecules and enhance LC behavior, but compensate for this by using the cyano group as one terminal function in the molecule. In this way the photochemically and chemically destabilising factor associated with earlier molecules would be eliminated. At the other end of the molecule we would use a flexible chain of carbon atoms in the form of an alkyl or alkyloxy group, and with some luck—that word again—some of the chains would lead to low melting points and stable room temperature Nematic LCs. As we will see this was an entirely successful strategy.

But first it should be asked, how did you know to do this?

The answer is that prior to undertaking this device oriented work in 1972, I had been doing fundamental research for over 20 years on how LC properties are influenced by molecular structure. I knew what I was doing by using the cyano group to compensate for loss of molecular length, while at the same time providing the strongly polar molecular structure needed for the electric field to switch on the display. This I stress was not luck. The strategy was based on sound factual knowledge established in earlier work on other systems in programmes of work described by some as academic, by which they mean lacking in objectivity, simply because they cannot see its significance. In other words, the fundamental science was secure. We understood what we were doing. And here I must digress to say how much it worries me to see money being so readily given to short term, mission oriented projects which have to have a new product just 6 months away—the so called wealth creating research—to the starvation of support for the fundamental science from which most outcomes of real commercial significance and benefit to mankind have developed over the years. Much of industry no longer seems able to fund such basic, investigative research. It has to be the academics who do such work, but even they are being pushed and persuaded into short term, mission oriented projects in order to obtain some financial support. This has to be resisted. Granted, some mission oriented work is needed, but a proper balance, and not to the detriment or extinction of fundamental studies. Academic research must not become a means of providing commercially saleable widgetts for industry. Academic-industrial partnerships are good, but only if based on mutual understanding and respect, and upon the real strengths of the partners.

However, returning to our main theme, the new materials—the cyanobiphenyls—we had produced proved to be excellent for the TN device. They could be used to produce quality displays operating at low voltages (2-5 V) suitable for battery operation, with minimum energy consumption in the μwatt range, switching in a few tens of milisecond. The displays were used first in simple direct drive watch displays, then in calculator displays of growing sophistication, until today when they appear in a vast range of everyday and scientific contexts. The displays were liked by users; demand was high, and since the materials provided by us were of high quality and stable, the devices had excellent lifetimes. So the now multibillion dollar LC Display Industry was borne and provided with a sound and secure basis given by a fine display mode and really good materials.

A number of points should be made at this stage.

1. The success of these materials was high and immediate because of the timeliness of their invention—just when the display needing such materials had itself

been invented. Discovered 2 years earlier, the materials would heve made no impact. Two years later, other alternative materials would probably have been produced by other researchers. That point is harder to judge, because many of the alternatives that did emerge during the next 8 years were in fact cyanobiphenyl mimicks or look alikes. Once chemists understood the strategy we used, cyclohexyl, phrimidinyl and dioxanyl analogues appeared. The point is however that to be of greatest effect, an invention has to be timely-again bringing in something of the element of luck or chance.

2. Production of a new class of commercial materials cannot be driven to maximum advantage by an individual or a University group. The success therefore owed much to the partnership we had with the Defence Research Agency at Malvern and the commercial producer of our materials—BDH Chemicals Ltd in the UK—now Merck (UK) Ltd. Without these alliances, the impact of the materials would not have occurred.

3. The importance of collaboration also lies in the ease with which development problems and new needs can be tackled swiftly. For example, when the molecules relax away from their upright positions, will they form a right or a left handed quarter helix? The answer is that they can do either and they do! If parts of the display go left handed and other parts right handed, nasty wall discontinuities occur between adjoining areas of opposite handedness, giving ugly lines across the cell. To counter this we made cyanobiphenyl compatible materials that were chiral, i.e., had either right or left handed asymmetry. Added to the device materials, a left handed additive ensured that the molecules would form a uniform left handed helix, thereby solving the wall discontinuity problem.

An amusing story can be told here. BDH Ltd sold commercially both Hull's right and left handed compounds. Customers could choose which to use. One customer decided to do better than everyone else and to use some of each additive. Of course the two cancelled out and the effect was zero-and he complained most bitterly that our products were no good. He had to be gently educated!

4. The rapid commercialisation of the new materials owed a great deal to the easy relationship which developed between the University chemists and the large scale industrial chemists and to the marketing skills of the staff at BDH Ltd. From the initial synthesis of the cyanobiphenyls in 1972 to the sale of the first materials late in 1973, only just over one year had passed—really a tremendous record.

To many, my big contribution to science will always be that earlier working making the cyanobiphenyls available for displays. Certainly it is the work which has made the headlines. Of course, although much of that was due to me, others—my research students at Hull, the researchers at DRA, Malvern, and the production and marketing units at BDH Ltd must take a lot of credit.

The story for my research group does not end here. Indeed this was but the beginning of a period running on into the 1990's when, coupling a nice balance of fundamental science and mission oriented research, we contributed strongly to the materials science of liquid crystals—providing new materials for improved operational modes of the TN display involving high levels of multiplexing or active matrix addressing and for new display modes as they emerged. Examples of these are Supertwisted Nematic Displays (STN) with memory capacity, Smectic A LC Displays and Ferroelectric Displays, the latter capable of microsecond switching. The Smectic A devices did not achieve commercialisation, and Ferroelectric displays have yet to emerge on the market, but that may not take much longer. TN and STN displays provide all the LC Displays of today's marketplace, and quite excellent they are, providing high quality coloured displays for computer and TV screens, including high definition capability in the projection mode of operation. Many of the products of this display technology are really most striking, and much of the device engineering is due to the skills of Japanese electronic companies.

Returning to the other activities of the Liquid Crystal Group at Hull University, parallel to the device materials work, we were developing fundamental understanding of the growing number of types of liquid crystal phase and discovering some of these ourselves. In other areas, we were researching on new chiral materials for thermochromic applications, and as a consequence of this we discovered the Gray-McDonnell Rules governing the relationship between molecular chirality and phase helicity-an interesting example of fundamental scientific knowledge stemming from a more mission oriented project. A lot of effort was also given to building up an understanding, as we had done for low molecular weight LCs, of the molecular structure/property relations for LC polymers.

With regard to this Award, although those parts of my work relating to the successful cyanobiphenyls must rate as very important, I would like to think that my choice as Laureate recognises too my continuing contribution over more than 40 years and including many different aspects, some of which I have already mentioned, but too numerous or technical to speak of here. One not yet mentioned would however be the development of novel synthetic routes to hitherto inaccessible LC materials. Others would be the writing of texts and reviews on LCs and working as Editor of the field's own Journal entitled Liquid Crystals. When I am asked personally what has been a highly significant part of my research, my choice is connected with the cyanobiphenyls, not because of their display uses, but because they are excellent room temperature materials and make available stable examples of Smectic, Nematic and chiral Nematic phases for physical studies. Hundreds of papers have been published on such studies made on our materials, the results of which have advanced enormously our understanding of the physics and dynamics of these fascinating, intermediate, ordered but fluid states of matter. The consequent development of man's knowledge is to me a source of great satisfaction, as of course have been the benefits to mankind stemming from LC Device Technology.

I would like to think too that the Award also recognises my work in nurturing the careers of very many young people who began their professional careers as my Ph. D. students and the work I have done and enjoyed doing as Chairman of the International Liquid Crystal Society. Indeed, I think that one of the nicest things that has been written so far about this Award was a reference to the service my wife and I have given in developing good international relationships in this area of science. We have certainly formed a wide circle of friends from very many countries, not least from Japan, a country whose people we respect very much for their motivation and commitment to hard work, for their courtesy, and for their philosophy of life. I have visited Japan several times, always with pleasure, and this is my wife's second visit. Last year, we said how nice it would be to return once again, but since my partial retirement over a year ago, the opportunities to do so seemed somewhat remote. The news of this Award therefore came almost as the answer to a prayer―the opportunity to visit Japan again, coupled with international recognition of the highest kind represented by this wonderful Kyoto Prize Laureate.

Finally, is there a message in all this for the young who aspire to achieving similar things? Obviously training and education are matters to be taken very seriously, and hard work and a single minded dedication are prerequisites. Luck and good fortune may be unpredictable elements in life, but at least their likely influence can be optimised by seizing every opportunity for the advancement of your aims and ambitions. In other words, never step back from an opportunity. Mistakes are inevitable in any career, but with a sense of humor, these can be laughed off, but while smiling, always firmly resolving that the same error will not be made again. Most important of all, be 100% professional in all that you do, paying scrupulous attention to detail and accuracy, and if you can, direct what you do to be of the most benefit to humankind. Finally, and very important, if you marry, choose as I did a partner who will advise you, be supportive of you and be prepared to tolerate the eccentricities which most of us scientists seem to have.

In looking over this list of success criteria, I think in fact that many of them apply very well to the young scientists of Japan whom I know, and this connects I believe with Japan's great strengths and achievements in science and technology.

However, International Recognition of the kind associated with the Laureate I have received can come to only a few, and many professional scientists and others give their lives to meritorious work which never receives proper recognition. There are not many Foundations like that created by Mr. Inamori, and I will always be grateful to him for his vision and philosophy in creating these Laureates and providing for me the most outstanding occasion in my entire career.

On this note I will end. I hope that you have learned something from what I have said and I thank you for your attention throughout this address.