The Relevance of Professor C. V. Raman to the Physical Theory of Musical Instruments

(Some Aesthetic Considerations)

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Having described the aesthetically delightful colour effects that light can produce in certain conditions, the distinguished American physicist Michelson observed: "These beauties of form and colour, so constantly recurring in the vivid phenomena of refraction, diffraction and interference, are, however, only incidentals; and though a never-failing source of aesthetic delight, must be resolutely ignored if we could perceive the still higher beauties which appeal to the mind not directly through the senses but through the reasoning faculty". This "aesthetic delight" is something more than a precise Michelsonian phrase. For it not only explains the nature of the scientific and literary achievements of the human mind but also highlights three scientific varieties of aesthetic sensibility. The first variety includes such achievements as Einstein's General Theory of Relativity, Bohr's Principle of Complementarity, Ramanujan's Notebooks, the Raman Effect, Dirac's Relativistic Theory of the Electron and Chandrasekhar's Limit. At this point, it is worth noting that the second variety is essentially a product of the culture of modern science. For it underscores masterly expositions such as A. N. Whitehead's *Science and the Modern World,* Albert Einstein's *Ideas and Opinions,* Neils Bohr's *Atomic Physics and Human Knowledge,* C. V. Raman's *The New Physics,* Werner Heisenberg's *Across the Frontiers,* James D. Watson's *Double Helix,* Peter B. Medawar's *The Art of the Soluble,* Prof. S. Chandrasekhar's *Shakespeare, Newton and Beethoven or Patterns of Creativity* and Steven Weinberg's *The First Three Minutes.* However, the third variety of aesthetic sensibility is derived from that unique gift of the human mind which can transmute a fundamental scientific problem or an elegant scientific exercise in aesthetics or even an interpretative piece of writing into a work of art. And this gift was possessed by physicist-mathematician-artists like Leonardo da Vinci, Galileo, Helmholtz, Rayleigh, Hardy and Raman.

To understand the life of Prof. Raman is to recall his own aesthetic moments. Incidentally, in his delightful book *A Mathematician's Apology,* the renowned English mathematician Prof. G. H. Hardy observed that "a mathematician's patterns, like the painter's or the poet's must be beautiful; the ideas like the colours or the words must fit together in a harmonious way". Actually, Prof. Raman was inspired by this quest for beauty in his scientific career. Indeed, Raman's scientific investigations on the blue of the sea, the optics of the pearl, the optics of coronae, the haloes and glories that often surround the sun and moon, the iridescence of a peacock's feather, the whispering gallery phenomenon of St. Paul's Cathedral, the harmonic content of the *Veena,* the sound of the drum, the physiology of vision and of hearing can be perceived as an exquisite symphony of light, colour and form, sound, harmony and rhythm. For example, the famous 1922 Royal Society Raman paper on the blue of the Mediterranean Sea recalls an aesthetic experience which is comparable to that recallable aesthetic sensibility that one can still experience in reading Galileo's *Starry Messenger* which recorded the first Galilean sight of a night sky through a telescope. And Prof. Raman belongs as much to physics as he does to the history of aesthetics.

The well-known 1963 scientific publication entitled *The Feynman Lectures on Physics* not only contains Prof. Richard Feynman's Caltech Lecture Notes, but also includes a Feynman photograph. This photograph dramatizes the distinguished American physicist, Richard Feynman—who, incidentally, has made the most significant contribution to quantum electrodynamics in our time—in an interesting posture. For it shows Feynman playing a drum with both hands. Indeed this photograph reminds one of the famous sketches which show Leonardo da Vinci trying to extract different notes in the process of beating a drum! Again, this photograph makes one remember the "spirit-stirring drum" of Shakespeare's *Othello*. Here, it is also well to remember that, apart from highlighting different types of single-faced and multi-faced drums—Bharata's *Mridanga*, Kalidasa's *Pushkara*, Sharangadeva's reference to the *Pushkara-traya* or a three-faced drum in the *Sangita-ratnakara* as well as the sculptural representation of a five-faced drum in the Nataraja Temple at Chidambaram—Indians had, over the centuries, been interested in the aesthetic variations of this play. In fact they had perfected a single two-faced drum known as the *Mridanga* or a pair of single-faced *Tabla*-s which can be played simultaneously, one with each hand. Furthermore, the Richard Feynman photograph reminds one of Prof. C. V. Raman, the celebrated Indian physicist of the heroic age of physics, whose scientific work ranged from the physical theory of musical instruments to the scattering light and ultrasonics. And though there is no Raman photograph associating him with a drum, it is worth noting that a major youthful interest of Prof. Raman centred round the physics and aesthetics of the *Mridanga*.

Commenting on the law of Pythagoras which formulated the mathematical ratios involved in musical harmonic relationships, Prof. Richard Feynman remarks[1] that "the general theory of aesthetics is probably no further advanced now than in the time of Pythagoras". He goes on to add in his chapter on 'Harmonics' that "in this one discovery of the Greeks, there are three aspects: experiment, mathematical relationships and aesthetics. Physics has made great progress on only the two parts". It is surprising that Prof. Feynman not only ignores a considerable amount of work in aesthetics (for example, Leonardo da Vinci's *Notebooks;* Mersenne's *Harmonie Universelle*, 1636; Kircher's *Musurgia Universalis*, 1650; Sir C. V. Raman's *The Acoustical Knowledge of the Ancient Hindus*, 1922; and Sir James Jeans' *Science and Music*, 1937) but also overlooks two fundamental publications in the history of physics—Helmholtz's *Sensations of Tone*, 1862, and Raman's monograph on *The Physical Theory of Musical Instruments* published in the *Handbuch der Physik*, 1927. Incidentally, this was the first time that the work of a non-German scientist was published in this prestigious series. Again, this invited paper was published by the German Physical Society at a time (the twenties) when the Germans dominated the world of physics. Actually these two publications embodied the Helmholtz acoustic institutions and the Raman acoustic investigations. Furthermore, it is worth noting that Kalahne[2] had reviewed Prof. Raman's investigations on the forced vibrations of strings in 1914. And these publications have inspired an entirely new area of research—or "the luminous melody of proper sound" to borrow a line from Wallace Stevens—which includes such developments as Prof. Raman's detection of musical overtones in the sound of some Indian percussion and stringed instruments. Prof. Raman's experimental verification of the Helmholtz conjecture that the speeds of the bow and the bowed point of the violin are identical as well as the adoption of modern electroacoustical techniques in the acoustical measurements of violins.

Leonardo da Vinci wrote in one of his *Notebooks:* "There is no certainty where one can neither apply any of the mathematical sciences nor any of those which are based on the mathematical sciences". What Leonardo wished to emphasize was the inadequacy of an observation of a natural phenomenon in qualitative terms. This thesis naturally reinforced the relevance of accurate measurements and quantitative relations to a study of natural phenomena. Travelling back in time, one notes the historic role of Pythagoras—in realizing that qualitative differences in sense perception are based on mathematical reasoning. Not surprisingly, the celebrated astrophysicist Prof. S. Chandrasekhar adverts[3] to just this relationship derived from scientific exactitude and aesthetic meaning in his lecture *Shakespeare, Newton and Beethoven or Patterns of Creativity:* "The discovery by Pythagoras that vibrating strings, under equal tension sound together harmoniously, if their lengths are in simple numerical ratios, established for the first time a profound connection between the intelligible and the beautiful. I think we may agree with Heisenberg that this is 'one of the truly momentous discoveries in the history of mankind'." Here one can also make a similar jump in time to the ancient Indian era, to realize how an equally ancient stream of aesthetics—for instance, that based on the acoustical perfection of the ancient Indian drum—bears what Prof. Raman noted as the "remarkable testimony to the inventiveness and musical taste of its progenitors." Again Prof. Raman wrote[4] in his essay *The Acoustical Knowledge of the Ancient Hindus* that "the study of the Indian musical drum and of the manner in which out of the most unpromising materials has been built up a genuine musical instrument which satisfies the most stringent acoustical tests and which even now stands on a pedestal high above the types of percussion instruments known to European music, leaves very little doubt in one's mind as to the highly developed artistic tastes and acoustic knowledge of the ancient Hindus". At this period it is necessary to refer to the origin of the word *Mridanga.* Actually Sharangadeva says in the *Sangitaratnakara:* प्रोक्तं मृदङ्गशब्देन मुनिना पुष्करत्रयम् (VI. 1025).

This means that "the sage has termed the three-faced *Pushkara* as the *Mridanga".* Furthermore, Bharata goes on to explain the nature of the *Mrittika* or mud in the *Natya Shastra.* Indeed, the ancestry of the dark material *Soru* (derived from a mixture of manganese dust, boiled rice and tamarind juice or a composition of fine iron filings and boiled rice which is shaped into the form of a disc on the right side of the *Mridanga*) can be traced to the following description:

नदीकूलप्रदेशस्था श्यामा या मधुरा च या ।

तोयापसरणश्लक्ष्णा तया कार्या तु मार्जना ॥

श्यामा स्वरकरी भवेत् ।

(*Natya Shastra*—XXXIV, pp. 114 ff)

"The application should be done with the fine, bluish and even silt deposited by water on the banks of the river. The dark silt makes the tone."

It is important to realize that Raman's interests in musical instruments and musical aesthetics were derived from his environment. His father, Prof. Chandrasekhar, was a professor of physics and an accomplished violinist. More importantly, Raman attended several concerts as a student of Presidency College, Madras, during the years 1900-1907. Among the musical luminaries of the time were Veena Dhanam (1867-1938) and Veena Seshanna (1852-1926) of Mysore. Here it is worth remembering that when Prof. G. H. Hardy's autobiographical work *A Mathematician's Apology* was first published, Dr. Ananda Coomaraswamy, in an essay, correctly argued that "it is with perfect right that the mathematician speaks of a 'beautiful equation' and feels for it what we feel about 'art'." Again Graham Greene wrote that, along with Henry James' *Prefaces*, Hardy's work reflected the sensibility of a creative artist. Similarly, Raman's essay, *The Acoustical Knowledge of the Ancient Hindus*, not merely constitutes an excellent account of the ethos of a creative musician in ancient India but is also a scientific essay in aesthetic interpretation which is relevant to the history of ideas.

It is a curious fact that several western percussion instruments are mere noise producers. To cite an instance, Lord Rayleigh had shown that the air enclosed in the shell of even the kettle drum does not specially contribute to any particularly satisfying alterations of the pitch relations of the musical overtones. However, Raman's ear for music detected musical overtones in the sound of the *Mridanga* which accounts for the fact that the acoustic properties of the Indian percussion instruments like the *Mridanga* and the *Tabla* are different from those of the instruments of percussion known to European science. "Times without number" wrote Prof. Raman, "we have heard the best singers or performers on the flute or violin accompanied by the well-known indigenous musical drums, and the effect with a good instrument is always excellent. It was this, in fact, that conveyed to me the hint that the Indian instruments of percussion possess interesting acoustic properties and stimulated the research". Indeed, Raman had demonstrated that the *Mridanga* could produce harmonics as a result of the heterogenous loading of its membranes. Moreover, since "the success of the arrangement depends entirely on the extent and distribution of the loading adopted and upon the arrangement provided by which the tensions of the membrane in eight different octants may be exactly equalized", Prof. Raman concluded that the acoustic properties of the *Mridanga* are not derived from mere chance but bring into play the distinctive signature of the Indian musical tradition. And more importantly, Raman had also demonstrated that a maestro like Palghat Mani Iyer (1912-1981) could make the *Mridanga* yield the near-equivalent to the sound of a stringed instrument.

In a well-known paper on *The Indian Musical Drums*, Prof. Raman pointed out that Indian musical drums (the *Mridanga* and the *Tabla*) "contained the solution in a practical form of the acoustical problem of transforming a circular drumhead giving inharmonic overtones into a harmonic musical instrument." As he remarked, "the drum has the special property of vibrating freely in different forms but with identical frequencies which can be superposed on each other. Some of the superposition forms have a striking simplicity, and indicate an analogy between the musical drums and the harmonic vibrations of a stretched string." Here, an attempt will be made to give an extremely simplified account of this paper. In this instrument, the drumhead is stretched over the open end of a heavy metal or wooden cylinder and carries a symmetric load distributed in five successive layers over a part of its surface whose superficial density decreases from the centre onwards. The load consists of a pliable and sticky mixture which contains finely-powdered iron. This produces an increase in the surface density of the membrane which is proportional to the thickness of the layer where the mixture is applied. There is, furthermore, a second membrane which is mounted in the form of a ring along the edge of the drumhead. A system of 16 tightening cords permits the drum-head to be stretched in all directions. This is very important for the correct adjustment of the pitch. The inhomogenous membrane so constructed has remarkable acoustic properties. The lowest tone and the first overtone of the drum arise from the vibrations without an inner nodal line and with a nodal diameter respectively. Both these tones are more or less in the ratio of a fundamental to its octave. The vibration with two nodal diameters has the same pitch as the vibration with one nodal circle, and is, indeed, exactly, the quinte of the first overtone. The pitches of both the next higher modes of vibration with three nodal diameters, and one nodal diameter and a nodal circle respectively are again identical and lie an octave higher than the first overtone. Similarly, three higher modes of vibration combine to yield the fifth harmonic overtone. These results have been achieved as a result of the careful arrangement of the load in the wake of the construction of the drumhead. As already mentioned, since some of the different modes of vibration have the same pitch, they can occur together as natural vibrations in any proportion and give rise to superposition figures. The inner lines arising from the superposition can assume the most varied geometric forms depending upon the ratios of the amplitudes. To cite an example, the nodal lines of the third harmonic overtone can have the following shapes: a circle, an ellipse, two parallel straight lines, two hyperbolic arcs or two diameters at right angles to one another. The fourth and fifth harmonic overtones can similarly give rise to other superposition figures, which can be experimentally detected from the equality of the pitch of the different modes of vibration. Among them are the interesting superposition figures for the fourth overtone consisting of three parallel lines and, for the fifth, four parallel lines. When the membrane as a whole vibrates, the fundamental originates; if it vibrates in two sections, the octave; in three sections (divided by parallel nodal lines) the third harmonic overtone; in four sections, the fourth and in five sections, the fifth tone of the harmonic series. Thus, some of these superposition figures present a remarkable analogy to the law of vibration of the homogenous string.

Viewed in historical perspective, Prof. Raman's work relating to the *Mridanga* and the *Tabla*-s is significant for us because it highlights a fundamental point, that the aesthetic meaning of an Indian concert must lie in some way in the relationship of the percussion instruments to the rest of the instruments (part to part, in actual terms) within a musically unified whole. For, this perception not only lends an aesthetic significance to the nature of the *Mridanga* and the *Tabla*-s in an Indian musical setting, but is also relevant to a study of the contemporary varieties of "Fusion Music". And just as the *Mridanga* and the *Tabla*-s are fused into the system of Carnatic-Hindustani Fusion Music (*Jugalbandhi*), so are they equally naturally fused into such varieties of East-West Fusion Music as the Sarod-String Quartet.

When a string vibrates, it produces a fundamental 'vibration' for which the length of the string corresponds to half the wave-length of the sound. The string, also produces other vibrations for which the length of the string corresponds to 1, 3/2, 5/2 wave-lengths. The frequencies of these vibrations are 2, 3, 4.......times the frequency of the fundamental vibration. If one could observe the vibrating string these vibrations have respectively 1, 2, 3, 4 stationary points or nodes. It may be noted that these vibrations which are called harmonics, overtones or upper partials are related to the fundamental frequency simply as the natural numbers. Obviously, the more harmonics there are the more 'musical' or pleasanter is the sound.

In the case of a plucked string, there cannot exist an overtone which has a node at the plucked point—as this point must necessarily move. Therefore, a series of harmonics is absent. Furthermore, the overtones of a plucked string fade out faster than the fundamental. Hence, the timbre is dull and hollow. This is especially so when the string is plucked with the soft part of the hand instead of with a plectrum. The latter gives rise to an entire series of overtones while in the former higher partial tones start dying off rapidly from the very beginning.

Of all the stringed instruments, the *Veena* has the pleasantest tone. Raman's ear for music detected the presence of overtones which normally should not exist in the case of plucked stringed instruments. Raman discovered that the bridge of the *Veena* has been so designed by the ancient Indians that both of the deficiencies mentioned above are overcome. In the *Veena,* the upper surface of the bridge is arched and the strings pass over it tangentially and do not make sharp angles with it. Actually, in this form of the bridge, the overtones do not die away faster than the fundamental, but, on the contrary, steadily increase in volume relative to it. Moreover, even the overtones which have nodes at the plucked point (which cannot exist according to Helmholtz's law) can be heard loudly in a *Veena.* These interesting effects were explained by Prof. Raman as due to the fact that, between the curved surface of the bridge and the string, the contact is periodic. This enhances the overtones at the cost of the fundamental through the regular series of impulses transmitted thereby.

The foregoing analysis is confined to the *Veena.* And, in order to understand the difference in tone-quality derived from the differences in bridge-formation between the *Tanpura* and the *Veena,* it is necessary to refer to Prof. Raman's paper on "Some Stringed Instruments". Here, Prof. Raman provided the following authoritative account: "The form of the bridge adopted in the *Veena* differs from that of the *Tanpura* in two respects. The upper curved surface of the bridge in the *Veena* is of metal, and the special mode of adjustment of contact by means of a thread used in the *Tanpura* is dispensed with, and the string merely comes off the curved upper surface of the bridge at a tangent. The bridge of the *Veena* is also much higher above the body of the instrument than in the *Tanpura.* Even when the strings are pressed down on the frets when the instrument is being played, the curvature of the upper surface of the bridge ensures the string always leaving the bridge at a tangent to it. . . . . In attempting to find an explanation for the difference in tone-quality produced by the special form of bridge, the author made a surprising observation, namely, that in the tone of the *Tanpura* or the *Veena* overtones may be heard powerfully which, according to known acoustical principles, should have been entirely absent. According to the law enunciated by Young and Helmholtz, if the string is plucked at a point of aliquot division, the harmonics having a node at the point of excitation should be entirely absent. This law may be readily verified on an ordinary sonometer with the usual form of bridge. For this purpose, the position of the node should first be found exactly by trial, by putting the finger in contact with the string and plucking elsewhere so as to elicit the overtones desired. Having found the position of the node, the string should be plucked exactly at that point and then again touched with the finger at the same point. On an ordinary sonometer, this results in the sound being immediately quenched in as much as the finger damps out all the partials except those having a node at the point touched, and the latter are not excited in the first instance in accordance with the Young-Helmholtz law. On trying the same experiment with the *Veena* or the *Tanpura*, it will be found that the overtone having a node at the plucked point sings out powerfully. In fact, the position of the plucked point hardly appears to make a difference in regard to the intensity of the overtones in the *Tanpura*. This remarkable result is not due to any indefiniteness in the position of the node point, as the latter is found to be quite well defined as is shown by the fact that, in order to demonstrate the effect successfully, the string must be plucked and then touched exactly at the right point, otherwise the sound is quenched. We are thus forced to the conclusion that the special form of bridge is completely to set aside the validity of the Young-Helmholtz law and actually to manufacture a powerful sequence of overtones including those which ought not to have been elicited according to that law".

"Some photographs of the vibration curves of a *Tanpura* string showed that as a consequence of the grazing contact at the bridge, the vibration of the string decreased in amplitude and altered its form at a much more rapid rate than when the grazing contact was rendered ineffective. From first principles, it is obvious that in the *Tanpura* the forces exerted by the string on the bridge must be very different from what they would be for a bridge of ordinary form. It seems probable that by far the greater portion of the communication of energy to the bridge occurs at or near the point of grazing contact. The forces exerted by the string on the bridge near this point are probably in the nature of impulses occurring once in each vibration of the string. This would explain the powerful retinue of overtones including even those initially absent in it. There will, in fact, be a continual transformation of the energy of vibration of the fundamental vibration into the overtones."

"The foregoing explanation of the character of the tones of the *Tanpura* would not be fully applicable to the *Veena* as the forces exerted by the string on the bridge in this case would not be purely of an impulsive character. There is, however, a certain portion of the bridge over which the string comes into intermittent contact during the vibration, and it seems very probable that the theory for this case is intermediate in character between that for the *Tanpura* and those for stringed instruments with bridges of the ordinary type. The tones of the *Veena* have a bright and pleasing quality and the special bridge in the instrument doubtless makes an important contribution to the observed result".

At this point my argument has, in a sense, to begin again. For, Raman's contribution to the physics of musical instruments not only brought out the unique characteristics of some Indian musical instruments which constitute a chapter in the history of music but also revealed a background of assumption that the generally accepted aesthetic concepts—beauty, unity, symmetry, proportion and harmony—can lend themselves to a scientific interpretation. In fact, Prof. Raman wrote in his *The Acoustical Knowledge of Ancient Hindus* that "at a very early period the Hindus were acquainted with the use of stringed instruments excited by plucking or bowing with the transverse form of flute with wind and reed instruments of different types and with percussion instruments. It is by no means improbable that India played an important part in the progressive evolution and improvement of these instruments and might have served as a source from which their knowledge spread both eastwards and westwards." Furthermore, his contribution possesses that supreme clarity, which is usually associated with fundamental work, to explain the state of the frontier discipline lying within the subjects of science and art as well as provide an insight into the nature of the quest for beauty in music.

Concerning himself with the abstract emotional correlates of formal aesthetics, Prof. Feynman makes the surprising observation that "we cannot still be certain whether the ear is matching harmonics or doing arithmetic when we decide that we like a sound". Here, it is relevant to quote a paragraph[5] from Sir James Jeans' *Science and Music* that wittily highlights the frontier between science and art. "If the question is debated as to whether the music of John Sebastian Bach is superior to that of his son Philip Emmanuel, science can bring nothing to the discussion. The question is purely one for artists, and it is quite conceivable, although perhaps rather improbable, that they may not be able to agree as to the answer. On the other hand, if the question is whether the music of either Bach is superior to that produced by a chorus of cats singing on the roof, there will be little doubt as to the answer. The artists will all agree, and science is able to explain to a large extent why they agree. To say the same thing in another way, the aim of music is to weave the elementary sounds we have been discussing into combinations and sequences which give pleasure to the brain through the ear. As between two pieces of music, both of which give pleasure in a high degree, only the artist can decide which gives most, but the scientist can explain why some give no pleasure at all. He cannot explain why we find the cat music specially painful." Thus, one is rightly led to infer that the connection between music and science is not merely a matter of the content of a musical work. However, Mr. P. J. Budden has a comment[6] on Bach in his chapter 'Groups and Music' which makes explicit the relationship between the concepts of musical creation and of mathematical patterns in a Bach-ian setting: "The fugues of the *Well-tempered Clavier,* a collection of forty-eight Preludes and Fugues for keyboard by J. S. Bach, are fine examples of this art form, providing a breadth of musical expression unequalled anywhere. Every device of counterpoint is to be found in the course of this masterpiece. The reader who has access to a copy will find Fugue 2 of Book 2 (in C minor) particularly rewarding to study. *The Musical Offering, The Goldberg Variations* and *The Art of Fugue* represent the culmination and perfection of the marriage of the art of the musician and the mathematician, but, again, the music always came first in Bach's mind, and the mathematical perfection arose inevitably and naturally, and the works mentioned offer a most rewarding field for study". And, it is also interesting to note in this context, Prof. Raman's comment on *The Subjective Analysis of Musical Tone* (NATURE, London, 1926) that "the power of discrimination is limited chiefly by circumstances depending on the physical character of the sound and of the auditory mechanism of the ear, rather than by factors dependent on nervous perception."

Prof. S. Chandrasekhar, in his *Beauty and the Quest for Beauty in Science* quotes[7] the following passage from Boltzman's aesthetic response to one of Maxwell's papers on the dynamical theory of gases: "Even as a musician can recognize his Mozart, Beethoven, or Schubert after hearing the first few bars, so can a mathematician recognize his Cauchy, Gauss, Jacobi, Helmholtz or Kirchoff after a few pages". This idea of recognition is indisputably central to any discussion of aesthetic concepts within the framework of science. To put it differently, the concept of aesthetic recognition reflects a variety of scientific and aesthetic responses, ranging from the determination of the Pythagorean comma and the acoustical measurement of the complete violin to an intuitive response to the western violin as a possible instrument for adaptation in an entirely different musical system. It is true that the subtlety of the performer and the ear of the listener are major factors in assessing the quality of the violin. Yet part of the answer is based on an investigation of some parameters—automatic bowing, Wolf Note of the violin, loudness, alterations of the tone produced by a Violin Mute. Actually, automatic bowing quenches the effect of the player and thereby enables one to determine sound output as a function of bow position, speed and pressure. This method of automatic bowing was pioneered by Prof. Raman in 1920. Here, it is also well to remember the memorable contribution of a renowned nineteenth-century South Indian composer, Muttuswami Dikshitar, who intuitively recognized that the western violin could be integrated into the system of Carnatic music during the beginning of the nineteenth century. Thus, the quest for beauty in science as well as in music is derived from a sensibility, which is at once scientific and aesthetic. In fact, the answer to this question has assumed several aesthetic categories of thought over the centuries—Pythagorean Harmonics, Alberti's aesthetic of proportion, Leonardo da Vinci's plea for scientific exactitude in studying natural phenomena, D'Alembert's Theory of Harmony, Helmholtz's Theory of Harmony, Michelson's 'aesthetic delight', Raman's aesthetic perception of the overtones of the Indian musical instruments, Chandrasekhar's concept of "the perception of the strangeness in the proportion and the conformity of the parts to one another and to the whole" and Dirac's feeling for beauty. And I would like to conclude with Dirac's answer to the question: How does one recognize beauty in a theory? The answer is especially significant since P.A.M. Dirac is a celebrated physicist endowed with an aesthetic mathematical mind who thinks that it is "more important to have beauty in one's equations than to have them fit experiment." And here is Dirac:[8] "Well—you feel it. Just like beauty in a picture or beauty in music. You can't describe it, it's something—And if you don't feel it, you just have to accept that you are not susceptible to it. No one can explain it to you. If someone does not appreciate the beauty of music, what can you do? Give 'em up! I have found, during the recent celebrations of Einstein's Centenary, that Einstein had very much this same point of view."

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