Darshana Jolts

Sound

V V Raman

Darkness is to space what silence is to sound, i.e., the interval.

– Marshall McLuhan

Its Variety: ***We hear all kinds of sounds.***

There is the serene chant of worship which lifts up the soul, and the magic of the mantra with its occult significance. There is the melody of music which fills us with delight and the hearty laughter which reflects a happy feeling. There is the cooing of birds and the gurgling of streams in rustic nature. There is the shriek of the frightened, the moan of the suffering, and the wail of the bereaved. There is the noise of the machine and the roar of the thunder. There is the private communication of whisper and the abrupt knock on the door. There is the chime of the bell and the bleat of the goat. There is the call of a familiar voice and the loud beat of the drum. One can go on and on, listing all the wondrous variety of sounds that fill our world of perceived reality.

Every sound touches our life in a different way, and connects us invisibly to our surroundings. Some evoke thoughts, some incite feelings, some create emotions, and others prompt jerky responses. Some give us delight, others evoke pity, some convey information, and others nothing at all.

We rarely pause to consider the countless ways in which we are affected by the myriad sounds that impinge upon us, if only because one does not ordinarily reflect on the common-place. Yet, sound is an extraordinary feature of perceived reality which adds depth and meaning to the world of experience in a hundred ways. Its rhythmic forms in poetry and prayer seem to put us in communion with some higher realm of reality, and its magnificent expression as music has been regarded as divine by many[1].

Something that is this relevant to human life, this significant an element in the world of perceived reality cannot be ignored in the scientific quest. Its roots need to be explored. Sound reminds us once again that there are elements in the physical world which affect our conscious life in unexpected ways.

[1] In the Hindu tradition one speaks of *gána-márga*, the path of music for spiritual fulfillment, as with the saint-composer Thyagaraja.

What is Sound? ***Vibrations of appropriate frequencies in an elastic medium.***

Sound, like light, is an inner experience, not a feature of the world beyond human existence. What is this ding-dong of the bell that we hear? There are two aspects to this question: First, we may wish to inquire into what in the external world is responsible for that which strikes us as sound. Second, we could ask about what is happening in the internal world underneath the skull that produces this sensation. Perceived reality consists of two parts: reality and perception.

Physics is concerned primarily with the reality aspect, and the physiologist and psychologist are interested in the perception aspect. Philosophers argue about the reality of the reality. But the physicist believes in a correspondence between aspects of the external and the experienced world: This is what creates the world of perceived reality.

Sound is not anything substantial that one can feel or see when one hears. It is a consequence of vibrations brought about in the surrounding. Sound is longitudinal pressure waves, so slight and subtle it causes no undue turbulence in air. The vibrations could be set up by any vibrating body: a drum or a string, a bell, the vocal cord or whatever can vibrate. Experienced reality may be static or dynamic.

Air is always disturbed to one degree or another by the motions occurring in it. By swinging a rope or a baton we can set up vibrations in air. We do not hear every swing because our sensory mechanisms respond only to frequencies within a certain range. It is difficult for human hands to shake a cane at twenty or more cycles a second: the minimum frequency for vibrations to be audible. Elephants hear low frequency vibrations. Mosquitoes can flap their wings fast enough to reach audible frequencies, causing the annoying hum of the beasties as they hover in our vicinity. We do not hear the much faster vibrations of atoms in solids, for there is also an upper limit to audible frequencies: about 20,000 hertz. Mice can hear such high frequency sonic waves[2].

What we perceive as sound consists of waves: in air, in water, in solids, or wherever, but waves in a material medium, and not in void.

The magic occurs when the waves reach our ears. The surface area of the normal eardrum is barely a sq.cm., smaller than a thumbnail. When the slight sound waves strike the eardrum, it begins to vibrate. Then through the wiring of neurons (nerve cells), powered by potassium and sodium ions, and assisted by fluids and bone-structure, the stimuli reach the brain where the physical processes get transformed into the experiential mode. Now we *hear* the sound.

[2] For more on these matters, see J Christopher Plack, *The Sense of Hearing*, Routledge, New York, 2005.

Loudness and Energy: ***Loudness is related to energy.***

The sweet whisper of a beloved and the firm order of a military commander are both sounds, as are the soft rustling of leaves and the roaring noise of a jet plane. But there are differences: especially in their loudness. Loudness is a feature of sound that strikes us most. Up to a point loudness is necessary for sound to be audible. It is also necessary for clarity. When a sound is both audible and clear, loudness beyond that is no longer necessary. It may become a downright nuisance, though it does augment the enjoyment of certain types of music. As we read in the lines of Lewis Carroll[3],

I said it very loud and clear;
I went and shouted in his ear.
But he was very stiff and proud;
He said, 'You needn't shout so loud!'

Recall that sound is a wave, and that waves transport energy. From the perspective of physics the loudness of a sound is merely an index of the amount of energy the sound wave carries: the louder a sound, the greater the amount of energy it carries. Compared to energy amounts that are involved in some other common contexts, the energy carried by sound waves is pitifully small. The marvel of the human ear can detect energy stimuli that are as low as a tenth of a quadrillionth of a joule per second[4]. If sound waves carried much larger amounts of energy, they would cause intolerable loudness, pain, and eventually deafness too.

It is interesting to consider energy inputs of such infinitesimal magnitudes. This reveals that at the root of perceived reality are processes that in sheer magnitude are minuscule in relation to what we are accustomed to. Even a meager candle burning for a few minutes puts out more (light) energy than does an entire orchestra playing for two hours. One author calculated that if all the sound energy from the noise of a subway train were bottled up for a thousand years and converted into heat, we will barely have enough energy to warm up a cup of water.

Physicists measure loudness on what is called the decibel scale[5] (dB). The faintest audible loudness is taken as zero dB. On this scale the loudness of a city thoroughfare may be about 60 dB, of a speeding train about 80 dB, and of an aircraft propeller about 120 dB. What is interesting is that the loudest sounds to which we are exposed carry a trillion times more power

---

[3] Lewis Carroll, *Through the Looking-Glass*., lines 15–18.

[4] This is 10–16 watts of power. See, for example, D R Howink, *Data: Mirrors of Science,* pp.90–91, New York, 1970.

[5] Other standard loudness units are the *phon* and the *sone.*

than the faintest. But such magnification in power does not create loudness explosions by similar factors[6].

The energy carried by a wave depends on its amplitude. More precisely, the energy a wave carries is proportional to the square of its amplitude. That is to say, if the amplitude is doubled, tripled, etc., the energy it carries becomes four times as great, nine times as great, etc. If the swings are greater, the louder becomes the sound generated. In the case of sound waves the amplitudes are unimaginably small. In fact they are of the order of the billionth part of a centimeter. This says something about the sensitivity of our perceiving apparatus.

Thus, in energy terms, the world of sound is modest in production but amazing in sensitivity. We expend only infinitesimal amounts of energy when we speak or shout. The physicist George Gamow once made an interesting calculation as to how much energy a professor spends when she delivers a one hour lecture[7]. It turns out to be of the order of a tenth of a joule. This much electricity would cost less than a millionth part of a rupee! The sensible moral we can draw from this is that it is not for the energy spent in producing the sound that we pay professors, but rather for the meaning and message in the sound produced. More than any other aspect of perceived reality, sound carries message and meaning. Therein lies its magic and its importance.

Pitch and Frequency: ***The pitch of a sound is related to the frequency of the waves.***

When one tries to vocalise musical scales it is an effort to produce as pure and clear a note as possible. A musical sound of a single pitch is referred to as a note. There are devices which produce sound of a single pitch.

But what is this experience we call the pitch of a sound? It is the frequency of a sound wave that is experienced as pitch. That is to say, pitch is the experiential dimension of how many times the wave oscillations occur in a given unit of time. Most of the sound that we normally hear is a complex of waves of different frequencies. In other words, we seldom hear a pure note by itself. Even the notes we hear from a musical instrument are made up of several sound waves with different frequencies, not all in the same amounts. By the phenomenon of interference these different waves combine to form a single wave: we experience the combined effect of waves of various frequencies.

It was only during the 17th century that the correspondence between pitch and frequency was established. Many experiments were performed in this context. Taking the length of a string

[6] This is why decibel is a logarithmic scale.

[7] George Gamow and John M Cleveland, *Physics*: *Foundations & Frontiers*, Prentice Hall, New Jersey, 1960.

fixed at both ends as representing half a wavelength, the frequency of the sound was fixed. And the puzzling thing was, how could a string of a definite length produce different frequencies. It was Joseph Sauveur who first realized that a string could vibrate in various modes: he called these harmonics. His work contributed much to the launching of the field of acoustics[8].

During the 18th century, the vibration of strings was theoretically analyzed by a number of mathematical physicists, especially Daniel Bernouilli and Jean Le Rond D'Alembert[9]. Their investigations led to many interesting results. At the same time the experimental study of sound vibrations on drums was carried out. In mid 18th century the tuning fork was invented. Credit for this goes to John Shore[10]. In the 19th century Karl Rudoplh Koenig who worked for a violin maker, began to design musical instruments. He invented devices using the tuning fork with which he explored frequencies associated with sound. Using the tuning fork Koenig constructed he could determine the absolute frequency of sound.

The Speed of Sound: ***Sound travels with a finite speed.***

We have all noticed that the clap of thunder reaches our ears only a few seconds after the flash of lightning blinds our eyes: from which follows the lesson from elementary school to the effect that sound travels slower than light. When we talk to a person, even at the far end of a hall, unlike the thunder from the distant sky, our words seem to be heard right away. Indeed we do not see any lack of synchronization between the movements of the lips and the sound they produce. This suggests that sound must be traveling quite fast. One may ask, how fast does it travel? How does one come to know how fast sound travels?

Once again we go back to the 17th century when answers to these questions were first found. In the first half of that century, Marin Mersenne (1588–1648)[11] and Pierre Gassendi (1592– 1655) made an experimental determination of the speed of sound[12]. Other experiments followed, like the one that William Derham did in 1708: He fired a cannon at one place and recorded how long it took for the sound to reach a point some twelve and a half miles away. His result yielded a value of 1142 feet per second. In 1738 the French Academy of Sciences arranged to have

[8] For more on Sauveur, see V V Raman, Joseph Sauveur, the forgotten founder of acoustics, *Physics Teacher*, Vol.11, pp.161–3, 1973.

[9] For more on D'Alembert's contributions to this, see V V Raman, Jean le Rond d'Alembert (1717–1783), *Indian J. Hist. Sci.,* Vol.19, No.3, pp.201–214, 1984.

[10] Watkins Shaw, *Oxford Dictionary of National Biography*, Oxford University Press, 2004.

[11] Allan D Pierce, *Acoustics: An introduction to its physical properties and applications*, Acoustics Society of America, New York, p.28, 1989.

[12] B Rochot, 'Gassendi (Gassend), Pierre', *Dictionary of Scientific Biography,* C C Gillespie, (Ed.) Charles Scribner's Sons, New York, 1970–1980.

cannons fired from Montmartre in Paris at half hour intervals, recording the sounds at Montlhéry about eighteen miles away. Their determination gave a speed of 343 meters per second. These are not very different from the currently accepted value. Interestingly, Isaac Newton determined the speed of sound analytically in his *Principia*[13].

Now think of what would happen if sound traveled at a much slower pace, say a few millimeters a second. Then when a professor is lecturing, students in the back rows will be hearing her much later: maybe a few minutes later than those in the front rows! The thud of thunder would be heard perhaps an hour or more after the flash of lightning.

In 1827 a bell was immersed at a point in Lake Geneva in Switzerland. When it was struck some gunpowder was flashed above ground. More than thirteen kilometers away under the lake a huge ear-trumpet with a membrane was immersed from which a tube emerged above water. From the observed time difference between the instants the flash was observed and when the bell was heard at this distant point, Daniel Colladon and Jacques Francois Sturm estimated the speed of sound in water to be about 1435 meters per second[14]. Jean Baptiste Biot's experiments gave the speed of sound in iron pipes.

One of the remarkable experiments in this context was the use of air columns for determining sound velocity. This experiment is still performed by students in laboratories. What is impressive here is that within the confines of a small room, indeed on a table top, using just a tuning fork and a hollow tube of adjustable length one can determine the speed of sound. Firing cannon balls is not needed any more, nor observations at points kilometers apart.

These are not the sorts of things we take note of in our histories. They are not wars and victories, nor political events or social upheavals, but they surely are adventures of the human spirit, conquests of the mind that enrich our understanding of the world.

Wavelengths of Sound: ***The wavelength of sound waves is of the order of common things.***

When we strike the middle C note on the piano we generate a sound whose frequency is 262Hz. Recalling the relationship between wavelength and frequency [*f*] we may calculate that this corresponds to a wavelength of about 1.3 m. The same note five octaves higher has a frequency of 8384 Hz, hence a wavelength of only about 4 cm.

Imagine for a moment that the wavelength of sound was of the order of a few millionths of a millimeter. Then, we would not be able to hear a person calling us from right behind us, let alone

[13] Isaac Newton, *The Principia*, Book II, Prop. 49,

[14] For details, see http://www.dosits.org/people/history/1800s/

a dog barking in a kennel or a prowler's stealthy steps, for the waves will not bend around to reach our eardrums.

This is a good example of how certain quantitative features of physical phenomena make us perceive the world the way we do. It is not simply the physical laws that create the impressions we receive, but equally the numerical values of their measurable aspects.

This recognition has provoked in the minds of some that the world was created such as it is for our benefit. The architect of the world designed sound waves commensurate with our dimensions so that we might be able to hear the cry of the baby from the next room; if not, wouldn't the child die of starvation? Leaving aside the fact that microbes manage to survive for generations without this benefit – they do not even hear, let alone listen to the music played in the neighbor's apartment – some have said that this argument is as valid as the view that our noses were made with bridges so that we might be able to rest our eye-glasses on them.

This is not to say that we should not take note of the quantitative advantages in the physical world which make human life an overall positive experience, and even be grateful to whatever or whoever made all this possible.

Resonance: ***Systems have their natural frequencies of vibration.***

When we hear certain kinds of music we begin to nod or tap our foot almost instinctively. There are common meeting points, as it were, which prompt us to respond with sympathy. As the poet William Cowper put it,

Some chord in unison with what we hear
Is touched within us, and the heart replies.

There is a physical phenomenon very similar to this. It is called resonance. Every system that can oscillate has a *natural frequency* of oscillation. The pendulum is the simplest example of this. When made to swing, a pendulum of a given length oscillates with its natural frequency (period). So does the child's swing in the park. The swing can be kept in motion only by being pushed now and again, or else it will come to a slow stop. Now, if the swing is given a periodic push at periods precisely equal to its natural period, the swing begins to oscillate with great energy: it is made to resonate. Resonance occurs when an oscillating system experiences a periodic force whose period is equal to the natural period of the system.

The effect of an applied periodic force may be to either oppose or contribute to the natural mode of oscillation of the system, depending on how well the force's own variation changes rhythmically with the natural modes of the system. If the applied force changes in a manner quite different from the natural frequency of the system, the most it can do is to force the system to oscillate like itself. If. however, the applied force varies in a manner very similar to the natural mode of the system, its effect will be to reinforce the oscillations, creating the resonance effect.

Resonance effects are quite common in physical structures. Particular attention must be paid to the aerodynamic stability in bridge construction. Architects take into consideration possible resonant effects due to winds when they design tall structures like skyscrapers. In 1952 several light fixtures vibrated violently in a newly built office in Los Angeles because their pendulum-like suspensions were set into resonant oscillations by earth tremors. The transmission and reception of electrical oscillations through resonance are basic to the functioning of radio and television. When we tune a radio we are making the circuit in our set resonate with one of the incoming frequencies. The periodic steps of a rhythmic march of soldiers could cause forced oscillations of a bridge; hence a standard order for soldiers is to break step before crossing a bridge.

When a string fixed at both ends is plucked, it vibrates with its natural frequency. Waves may be set up in a cavity with air in it. The cavity will have its own natural frequencies. That is to say, waves of well-defined frequencies can be generated in it with greater ease than other waves. Such a cavity then becomes a resonator. Resonators are attached to most musical instruments. The vibrations set up by strings on the violin are picked up and reinforced in the resonating cavity, creating the melodious sound we hear.

Echoes: ***Echoes are used by some creatures*.**

There are creatures for which echoes are essential for their survival. Lazzaro Spallanzani (1729–1799) was a prolific scientific investigator of the 18th century. In 1794, when he was a sexagenarian, he did some experiments with bats. He blinded the poor animals and found, much to his surprise, that this did not deter them in the least in their flights! He jumped to the conclusion that the creatures had a sixth sense which enabled them to detect obstacles on their way[15]. Others found that the bats did not fare all that well when their ears were sealed. The suspicion arose that the ability of bats to locate obstacles had something to do with their hearing. But it took almost a century and a half before the matter was fully exposed. Donald Griffin and Robert Galambos discovered that bats emit high frequency pulses whose echoes make them aware of obstacles on the way[16].

---

15 For more on Spallenzani, see Paul de Kruif, *Microbe Hunters*, Harcourt, Orlando, FL, 1996.

16 D R Griffin, *Listening in the dark*. Yale Univ. Press, New York, 1958. Though dated, it should be consulted in this context.

Porpoises are able to spot obstacles even in muddied waters thanks to the echoes they receive of the very high frequency sounds emitted by them. In the early decades of the twentieth century Paul Lengevin tried to utilize echoes from ultrasonic waves to locate submarines[17]. Today the application of this idea has evolved to considerable sophistication: this is the basis of sonars and ultrasonic photography which enable us to chart the depths of seas and determine the sex of unborn fetuses.

Applied to electromagnetic waves, this becomes radar: yet another gadget, of 20th century technology, which serves a wide range of purposes: from spotting speeding cars to detecting clouds and hurricanes, so useful in weather prediction. Radar has also been used to determine the distances of celestial bodies.

Music and Noise: ***There is a fundamental difference between music and noise.***

When the English wit Samuel Johnson quipped: "Of all noises I think music is the least disagreeable," he was not using the terms in their technical sense, because music cannot be considered a noise any more than that a random complex patch of lines may be regarded as a geometrical form.

At the experiential level the difference between music and noise is clear: we enjoy one and find the other not so pleasant. Musical sound and noise are both composites of waves, with this difference: musical sound consists of discrete frequencies, whereas noise is made up of a continuous set of frequencies. It is somewhat like the difference between a can of pebbles and a can of flour. In the one case we can separate out the components, literally count them as so many; in the other case, it is one continuous pack of indistinguishable parts practically touching one another. In a musical sound, such and such frequencies are present. In noise, practically all frequencies are present.

A spectrogram displays the component frequencies in a given sound. The spectrogram of a musical sound would reveal straight lines corresponding to the frequencies that are present, whereas we will find a whole continuous patch in the case of noise.

Now consider a certain tone, say the middle A of 440 Hz. Corresponding to this fundamental frequency there are higher harmonics as well. When this note is sounded in a musical instrument, higher harmonics are also present to some degree. The relative amounts of the various higher harmonics present when the note is sounded will depend on the instrument in

[17] Isaac Asimov, Paul Langevin, *Biographical Encyclopedia of Science and Technology*, Doubleday & Co., Inc., 1972.

question, because it is a function of the shape, size, material, mode, etc., of the resonating cavity. As a result, the same note sounds very different when played on a sitar, a harmonium, or a flute.

This is also true of the voice box or any source of non-musical sound also. That is the reason why there are distinctive differences between the voices of different people. Each individual has his or her own characteristic voice spectrum. Like the fingerprint which is unique to the individual, we have our own voice prints: a vocal signature of our individuality. This has been used in the forensics[18].

It is remarkable that these differences can have such varying effects on our perceptions. Music is soothing and pleasing; noise is not. At the tactile level, the situation is different: it is the smooth continuity of a surface that causes the pleasing sensation of a soft silky touch. Discontinuities as on a surface with peaks and sharp protrusions, as in a bed of nails, are certainly not enjoyable.

Music of the Spheres: C*elestial music is a beautiful metaphor.*

The idea that associated with the celestial spheres that move in harmony in high heavens there is a cosmic music that fills the universe is quite old. Ancient Hindu thinkers had imagined the universe to be pervaded by magical mantras: divine poetry with spiritual prosody and esoteric significance. These nuggets of eternal wisdom were revealed to Himalayan rishis as the Vedas: the scriptural treasures of Hindu culture. When Moses heard the Commandments and the Prophet the Holy Koran, they too were privy to this cosmic music.

Even as strings plucked in proper proportions produce the various octaves on the scale, planetary motions in conformity with celestial arithmetic must create a divine music: so went the reasoning. The imagery was beautiful. The spheres were heavenly wheels on each of which stood a sweet siren (an alluring nymph) who created a musical note. It is the combination of these notes that merged to form the music of the spheres. The Pythagoreans believed that the great Pythagoras was one of the few who could hear this music. Others, perhaps in the mother's womb or in early infancy recognize it, but age and corruption soon deafen ordinary mortals to this universal harmony. Aristotle who believed the heavenly bodies to be perfect crystalline material is said to have heard that the delicate perfection of cosmic crystals would be shattered by such loud notes in heaven. These became the Muses after Plato's school was formed, and Christian mythology transformed these into angels and other celestial beings who formed a

[18] See in this context, H Hollien, *Forensic Voice Identification*, Academic Press, San Diego, CA, 2002.

celestial orchestra. The notion of the music of the spheres was taken quite literally even by Kepler in the 17th century.

Underneath the poetry of the ideas there is the insight that as music is intrinsically wedded to mathematics, so is our understanding of the universe at large. As scriptural wisdom is the key to an understanding of the nature of the universe (in the traditional mode), so is the mathematics of astronomy.

From current perspectives, it is difficult to imagine music in stellar space if only because we need an elastic material medium for sound. No one can sing on the moon, and even if one beats a drum with full force no sound will be created there, for the moon is without atmosphere. So all picturesque and poetic talk of music in the heavens is really not physics as we understand it.

And yet, in a strange sort of way, the idea has a modern analogy. In 1966 astronomers discovered a microwave radiation that is cosmic in scope that has been there every since the birth of the universe. This surely is not sound, nor music in the usual sense, but there is an all-pervading vibration in the heavens: a notion that would have seemed strange and unacceptable to the physicists of the 18th and 19th centuries. Ultimately, in our own times in the worldview of string theory, the fundamental particles (the material substratum of the universe) are essentially supersubtle strings vibrating in different modes.

***

Previous Parts:
The World Above: Vol.15, No.10, pp.954–964; No.11, pp.1021–1030, 2010;
The Physical World: Vol.15, No.12, pp.1132–1141, 2010; Vol.16, No.1, pp.76–87, 2011;
On the Nature of Heat: Vol.16, No.2, pp.190–199, 2011;
Sound: The Vehicle for Speech and Music, Vol.16, No.3, pp.278–292, 2011;
Light: The Revealer of Chromatic Splendor, Vol.16, No.4, pp.359–371, 2011;
More on Light, Vol.16, No.5, pp.468–479, 2011; Vol.16,
Matter: The Stuff the World is Made of, Vol.16, No.7, pp.670–681, 2011;
More on Matter, Vol.16, No.8, pp.784–793, 2011; No.10, pp.987–998, 2011; No.11, pp.1061–1070, 2011;
More on Force: Vol.17, No.1, pp.83–91;
Waves: Vol.17, No.2, pp.212–224, 2012.

V V Raman is Emeritus Professor of Physics and Humanities at the Rochester Institute of Technology, Rochester, New York 14623, USA. He is available for giving Skype lectures in Indian universities. Email: vvrsps@rit.edu
http://en.wikipedia.org/wiki/Varadaraja_V. _Raman