ACCOUSTICAL AND OPTICAL WAVES: A CONFOCAL POINT IN PHYSICS

by

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Any perception of a world image is gained by the perceiver from his localization in a point of what may be viewed as a generalized phase space, a space whose coordinates could be difficultly undergo a precise definition, but whose existence is at the basis of our very consciousness of being. The successive knowledge of the structure of this space through the acquaintance of others' experience works on us in producing a kind of matched filter that in some way isolates an objective image of the world out from our subjective approach.

In this process of making our experiences objective, a parallel process is set up for correlating different aspects of reality, which is the process of synthesis that has been given different names, as science and art, to name the evoluted ones. An effort for synthesis is intrinsically present in any act of ours of knowledge and a texture of roads can be traced in our way of getting to a description of reality, that we often walk over again in the attempt of implementing what we know with that which we struggle for knowing. The question then arises as to whether new syntheses would come simply from the search of new ways for synthesis, since the way is so intimately connected with the target, as the thesis is with the assumptions.

To experiment new ways for a synthesis of knowledge, or to use old ways for further developing it is a step that is markedly welcome in the attempt of ascertaining the validity of a result, or of an objective perception of a world image.

As a matter of fact, we connect fragments of knowledge, that *finally merge into a theory or into an image of the world, that may become in turn a passage for new or larger syntheses to come.*

In the realm of science, concepts are encountered which project their shadows on a number of disciplines and which, conversely, imply the use of tools elsewhere developed for a full interpretation of their phenomenology. These are marking points in the construction of a scientific knowledge: they are main roads in our process of synthesis, to which we naturally refer for new or broader syntheses.
Waves is one of such marking points: its territory belongs to the field of physics, but it was a concept well before physics embraced it, and it well extends its implications onto the outside.
Might it be due to the unique position waves enjoy with respect to the interface of man with the outside world, in as much as they serve as the principal means for getting in touch with what is outside of him, they diagonally cross the history of science and they lend today themselves to the interpretation of the probability of nature states.
No branches of physics, indeed, are so tightly connected, in their origin, with the physiological interaction of man with nature other than optics and acoustics. In a sense, hearing and seeing, in supplying man with information about his enviroment, have themselves constituted natural fields of investigation,

from which successive developments stemmed toward comprehending a rich phenomenology, which often might be hardly recognized to belong to anything connected with the ear or with the eye. Earthquakes and sonic bangs, holography and X-ray diffraction by crystals, ultrasonic echography and noise control, fiber optics and ionospheric radiowave propagation, not to say but of a few phenomena, seem to share not a single fragment of knowledge one with the other or with hearing and seeing. But what is common to this wide variety of phenomena is the elementary concept of wave, i.e. of the way in which points in space at different times participate of the same state of motion, in a general sense.

The way in which the perturbation produced at one point in space spreads over to other points is ultimately bound to the kind of perturbation produced or, better, to the response of the medium to the perturbation itself. In this respect, it is in some way intriguing the fact that the stress field in a medium and the electromagnetic field in vacuum produce waves in a very similar manner, by linking together in a constant ratio the space gradient of the field with its time variations. In the acoustical case, the constitutive equation of the medium supplies the Newton equation of motion with the proper space-time variation, while in the electromagnetic case, it is the Maxwell reciprocity between the electric and the magnetic fields that leads to the wave equation. This is a common point *of arrival and, by reverse, a common starting point of acoustics and optics.*

In the attempt of producing a synthetic view of all the wave phenomena and trying to extend the view elsewhere, let us consider deeply what is intrinsic to a wave process. The common idea of a wavelike figure in space or of a periodically oscillatig quantity in time may render the idea of a wave, but it is quite unsufficient for its exact comprehension, since it is inherent to a wave process that subsequent events in time at a certain point in space should replicate with a definite delay the series of events at other points. Propagation is, then, the specific attribute of a wave process; and, with it, the velocity of propagation, as the ratio between space distance and time delay of points identically perturbed. Bound to velocity, there is the problem of the characteristics of the medium that supports the wave and the stimulating question concerning the case of vacuum, as a supporting medium for electromagnetic waves, that sets its specific velocity on the basis of the links in the structure of space and time.

A wave, then, is the fundamental way in which "information" may be exchanged between different points in space, or "observers", to use a terminology closer to our human state. A continuous way of transmitting information, indeed, may be set through a wave channel and there is no wonder, then, that our exchange of *information with the outside world comes mostly along wave channels. Words and images are perturbations of physical systems, used as terminals or receivers of waves elsewhere generated. Energy is transduced into a wave at the source localization and waves go back into other forms of energy at the receiver's localization. No differently travels the information along the stimulated nervous system inside the body, where sources and detectors localize at the peripheral and central regions of our body, respectively; no differently travel the signals along a telephone cable back and forth between two intercommunicating users or a TV message from transmitting and receiving antennas.*

By reverse, then, a question may arise, as to whether information needs a wave for being exchanged. Certainly, biological systems define their future states on the basis of conditions, which are known through messages sent in the bulk, via material mediators: thus, they stand as evident antiexamples of the presumed assumptions. However, even without making any appeal to the obvious statement that any microscopic interaction between particles is ultimately mediated by a field particle and may therefore be represented by a wave, I would like to point the attention to the rate of information that a wave allows to exchange. The amount of information, indeed, that a wave may carry along is only limited by its frequency, according to the Wiener's theorem of waveform sampling; and the frequency of a wave has no theoretical limitations, so that the actual *limitation of a channel information rate capability resides on the limitations of physical sources to produce and physical receptors to detect the signal itself.*

There is, therefore, a most evident offer of waves to be used as privileged means of information exchange between physical and biological systems. Waves seem to stand as privileged means even in so far as the dynamical range of the communication channel is concerned, that is as the maximum acceptable excursion of the energy level of signal to be transmitted. In this respect, I would like to recall that background noise usually is the limiting factor of any transmitting channel at low signal values and nonlinearity is the limiting factor at high ones. Regarding noise, anyway, it should be mentioned that wave transmission is "tunable", that is all spurious signals or disturbances having different frequency, or "marks", from the considered one can be filtered out: it is a very favourable fact that our eyes do not react to infrared radiation and do not see the warm air in between the objects! Therefore, the level of a signal to be detected can be very low, since it may be compared with the amount of noise which is present in a restricted band of frequency values and, theoretically, its limit is set by the same limit that the classical interpretation of nature shares, since it is the zero point energy that has to be taken as the noise level.

At the upper bound, nonlinearity is the second barrier: in this *respect, it is really a very favourable fact that vacuum is a linear medium for electromagnetic radiation. That is, no synergetic effects are produced by electromagnetic radiation in vacuum and what is produced on a distant galaxy as a signal undergoes no sort of variation in the wave shape, when we receive it on the Earth.*

Neither are effective in space dispersion effects: there are are no objects in vacuum that set a measure to the wavelength and waves of different wavelengths travel with the same velocity, thus letting a complex waveform to travel unaltered along its propagation path.

Let us think over for a while on this undistortion process we have implicitly described: linearity permits to a wave to maintain its shape, because different heights of it are transmitted unaltered from one point to another; the lack of dispersion makes all points of the waveform to move synchronously along space. Both processes work to maintain to a wave its shape. However, if vacuum is a linear and dispersionless medium for an electromagnetic wave, this is not the case for material media, both for electromagnetic and elastic waves. To our means of communication, however, we see and hear mostly through air, and air is almost vacuum for light and time and space sizes of its microscopic constituents are uneffective to the proper times and spaces of the acoustic wavelengths we are sensitive to. Waves, then, present us with undistorted images of the outside world.

In any process of knowledge of ours, distorsion is a biasing factor that deteriorates the information content of a signal. It comes into act at points where a piece of information is received and transmitted to other points; the uniformity and equity in releasing the acquired information is warranty for undistortion. Distortion acts as a noise source in the process of information exchange through wave propagation; however, differently from random noise sources, it can be accounted for - once that the medium effects are known - by proper deconvolution processes of the received signals. No differently, sometimes we try to unveil the distorted truth of news we receive through unreliable sources of information, by filtering out what we think has been added or has been overemphasized. But we ought to know which source of information we have! We ought to know the properties of the channel we are using! And the channel has to be known independently, either by sampling it repeatedly or through past experience of its convolution properties.

Once that a world image faces linearly our sense organs, it has to be received, or transduced, and then processed. Although it is not in the purpose of this work to trace the story of the sensory information process, it is interesting to note that the transduction process of a wave signal operated by the physiological senses is no longer linear. A short remark is worth to be given to the similarities in our senses of sight and hearing, relative to the Weber-Fechner law of logarithmic *sensibility, for which the minimum variation in the energy level of a signal that could be appreciated is proportional to the energy level itself, in such a way that physiological reactions are constantly normalized to the average value of the received signals. Masking effects and the double replication of the organs are additional evidences of the similarity we have in the physiological approach to the outside world.*

The linear response of the propagation medium greatly simplifies the mathematical treatment of the wave process. As a matter of fact, a nonlinear propagation equation cannot even be called a wave propagation equation: this is such only in the limiting case of setting the nonlinear parameters equal to zero. However,in case that slightly nonlinear terms are present, things are still tractable and a new phenomenology of wave propagation appears, such as harmonics and subharmonics generation, parametric coupling between different channels, nonlinear disersion and solitons.

A number of facts, phenomena, interpretations, procedures, principles has been drawn in this field, such that it can hardly be thought of another field where more evident is the texture of roads which has been previously mentioned to lead to new description of reality.

I would like to synthetically quote from a scientific work by Wiener Lautherborn, that, if a physicist at the turn of the century would have been asked what the essence of the world was, *he would have answered: "The world is statistical", in view of the unification of the mechanics and statistics done at that time. But, ten years later, he would have probably answered "The world is relative" and twenty more years later "The world is quantal". What is there to add, today, at a distance of fifty years? What can be expected to become the next fundamental step in science probably is nonlinearity. It is fundamental in every process of nature, although it has been given scant consideration, but in few cases. I would like to add that nonlinearity is the general law in human behaviour and in the social sciences, where the response of systems - although not easily subjectable to a quantitative evaluation - seems to be related in a nonlinear way with the perturbing causes.*

The reason for setting aside in the past the problem of nonlinearity was not as much the smallness of the effects nonlinearity produces compared to what linearity is responsible for; really, the discriminating incidence in the line of thought between linear and nonlinear phenomena relies in the lack of structure the latters have: solutions to nonlinear problems seemed to be found one by one, with no real possibility to end to any generalization.

Presently, the situation is drastically changing, with the recognition of similarities in nonlinear solution of problems, that are building bridges between different parts of sciences.

A soliton is a stable, pulse-like, localized, solitary wave with peculiar interaction properties with other solitons that give it the character of a particle. As it is the case for all nonlinear processes, superposition principle does not hold for solitons; however, special solutions to the problem of nonlinear propagation have a general meaning, and solitons form, in a certain sense, a complete set of solutions and can therefore be considered as the elementary excitations of nonlinear systems, in a more or less similar way that harmonic waves are in linear processes. Solitons incidence in fundamental physics is getting increasingly higher and I would like just to mention the problem of damping of sound waves in crystals at the microscopic level, which relates to the problem of energy partition among different degrees of freedom and, therefore, to the equilibrium approach of a system.

I do not want to enter the topics of deterministic chaos, which is another fundamental structural element of nonlinear physics, because it would deserve much more than a paper by itself and because it goes far beyond the problem of wave propagation. Let me just simply recall that the problem of turbulence, which has long been known in hydrodynamics and underlies the setting of deterministic chaos in nature, has entered the fields of optics and acoustics and that interesting insights into the general problem are coming today from models, that may be easily tested with optical or acoustical waves.

If energy sets a limit to the wave field variables for the *problem of wave propagation to be reduced into linear form, no sort of limitation is set in terms of frequency and wavelength. Down from zero, up toward infinity, acoustical or optical waves behave uniformily and, as a matter of facts, it is the extension of the frequency range from the audio and the visible ones to all possible values that has enlarged the perspective of the original disciplines of acoustics and optics to encompass completely new territories of the physical sciences. Thermal phonons are acoustical waves whose wavelengths compare with the distances of atoms in a crystal grating and gamma rays may range even shorter. The scaling factor for wavelengths, however, requires new technologies for the generation and detection of waves: the complete similarity in the propagation of both acoustic and electromagnetic waves at any conceivable frequency breaks down into a variety of means used for transducing the energy that is bound inside a physically limited object into a radiated wave. Loudspeakers and interdigital surface acoustic wave transducers are in no way related ones to the others, as LC-circuits are not related to laser cavities. However, one can find a series of concepts that links apparently different phenomena, throwing new light on unknown facts. And I would like to review briefly some of them, in the attempt of bridging different pieces of knowledge apparently not related, and implicitly suggesting different interpretations in other fields.*

The coherence of a wave is a measure of its being equal to itself at different points in space and instants of time: it is the requirement set on the phase to grow uniformily, with no jumps or drifts. It is strictly dependent upon the way in which the wave is generated by the source. Obviously enough, the generation itself of a wave is a modification of a physical state and the longer is the act of generation, the higher is the coherence length of the wave.

The effort for getting higher frequency coherent radiation is being continously done in optics through the search of new lasering media and systems, and in acoustics by the advances in microelectronics and in photolithography. High frequency and coherence, indeed, are both very valuable requisites for a transmission channel, since the former potentially opens the way to high rate of information transmission, and the latter makes it actual, in a certain sense, such a potentiality, by marking the wave with a reliability certificate that no random fluctuations are possible. But high frequency and coherent characteristics are no easily attainable contemporarily. To produce a continuous wave train of a single frequency, indeed, it is required that each emission act of radiation from a source be stimulated by the wave itself, so that successive quantum bunches of radiation be connected one with the other with a proper phase relation that makes the wave to build up continuously. This mechanism is frequency sensitive and does not easily allow for the realization of high frequency coherent wave *radiation.*

Coherence is a term clearly borrowed from everyday's language, and it reflects the reliability offered by a person or by a system to behave in a predictable way. No differently, in the physical sense, the amount of information that can be given to a coherent wave greatly extends with respect to an uncoherent one: the exact knowledge of the phase behaviour being an additional point for implementing the storage capability of a wave. A coherent wave can be used as a reference for mixing it with a signal and etherodyning detection of radio receivers and electronic equipments, together with holographic recording of optical or acoustical waves, are evident exploitations of coherent wave capabilities.

The propagation of a wave in a medium is affected by the inhomogeneities that are present along the propagation path, and absorption is the overall effect that is produced by a random distribution of inhomogeneities. However, if the inhomogeneity is represented by an abrupt change of the physical characteristics orderly distributed on a surface, that is then the problem of refraction that comes into place. The energy carried by a wave that impinges on a surface of discontinuity between two different media is split into a part that goes over into the second medium, and into a part which bounces back into the first one. The amounts of energy that the wave is split into are determined by the specific impedances of the limiting media.

Impedance, indeed, is a new concept that is largely used in wave propagation and that seems to undergo more general definitions.
A force - we know - produces on a body a proportional time variation of its linear momentum or, in a simplified version, of its velocity time its mass. However, if a force is given by the field gradient of a potential, it may continuously act on a flow of particles moving them through a viscous medium. In such a case, the force is linearly bound not to the velocity derivative, but to the velocity itself, like the flow of electronic charges in a conductor or a fluid flow in a pipe, and the proportionality factor acquires the characteristics of the impedance of the medium.
In wave propagation, a field variable, like the velocity of the material's particles in the acoustic case, is caused to change linearly with the acting quantity, like the stress field. At the limiting surface between two different media,the continuity conditions on the stress field, or the acting quantity, makes the energy to split into parts related to the specific impedances. The concept of impedance is not greatly altered in the more interesting case that wave is generated or received at a transducer site. In this case, energy is not really subdivided between two different media, but it has rather to be introduced from one system to another: it should be transfered from the wave to the transducer, or vice versa. At this points, indeed, a wave must encounter an adapted impedance in order for energy to be transfered to the receiver or, vice versa, the source has to

match its impedance with that of the propagating medium. Impedance matching, then, becomes a most important factor in high efficiency of energy transfer and we all know that our middle ear's ossicles behave like an impedance matching circuit from the outer to the inner ear, from the air propagation to the fluid propagation of waves in the cochlea and we are all aware of the bluish colour that good quality lenses show for impedance matching purpose between air and glass propagation.

Still connected with the interacting characteristics of systems with waves, both at the sources and at the receivers sites, is the capacity of processing signals of different frequency values. Technicians call this property the time-bandwidth product of a system. Though it is not a direct concept to be intuitively understood, part of it, one factor of it I would say, the bandwith, is an easy one to grasp and it may well be mentioned for spilling it over into other areas of science.
Bandwidth is the range of frequencies within which a system is sensitive to external perturbations or, conversely, it is the range of frequencies which a system is capable to generate. If we think at the resonances we sometimes observe in a car when we are driving it at a certain speed, we realize that systems get into and out of resonant conditions, as the perturbing cause drifts over a certain range of physical parameters. If we act on an oscillating system with a driving frequency that continuously changes over a wide range of values, it will respond and get

into an oscillatory motion only if the frequency does not differ more than a fixed amount from a specific frequency, called the resonant frequency of the system, and the oscillation amplitudes peak at this value, smoothing down the farther we move away from resonance.

The quality factor, or the Q value, of the system is the ratio between the central frequency value and the bandwidth: while the resonance frequency is determined by the way and the rate at which the energy oscillates within the system from one type to another, the bandwidth is due to irreversible processes through which that energy is leaking away from the system into other forms.

Once again, then, interaction with the outside world is defined by a system parameter - its Q or quality factor - that is a direct measure of the energy exchange rate of the system with its surrounding medium. Line widths of light spectra emitted or absorbed by microscopical physical systems, radio receivers' tunable circuits, auditory and visual receptors, oscillating structures, resonating electromagnetic cavities, etc., do all undergo a Q definition.

The larger is the Q of a system, the more restricted are its possibilities of interaction with other systems and the longer it keeps staying in the same physical state. The mood of exchanging energy with others makes one system's states less endurable, in agreement with the uncertainty principle of quantum mechanics, that an exact definition of the energy level makes a state to endure undefinitely.

The Q factor partially is a result of impedance matching between the system and the surrounding medium, and the generated wave has its coherence determined by the lasting of the generation process, which is a result of the system bandwidth. In the background of these concepts, we recognize the shape of the uncertainty principle of quantum mechanics, or simply the wave analysis product Dx*Dk between space and momentum intervals.
Wave physics, then, has been seen to move within frameworks where concepts find links in even more general frameworks. But the breakdown of concepts is a way, or a justified operation, for testing whether the reasoning produced in one field of human knowledge is effective in other fields. Perhaps, we should firstly question whether the modelling of reality, which we operate on our perception of it, is intrinsic to reality or to our knowledge, so as to convince ourselves that some good can be derived from such an operation.
But the limit of a nature scientist, as the author is, lies in producing hypoteses of knowledge and that may, in turn, seem to privilege the thing-language with respect to the ontological synthesis of concepts. The search for unification, however, may not stem from the description, but from the interpretation of facts: it relies in the effort of finding structural relations that may lead to general models or theories.

Can that be reached from the analysis of a sector or a fragment of science, as the wave physics that we have discussed? Although we do not know the target of the synthesis process, this way surely appears to be limited. And it certainly is. But it is the actual disposition of the cognitive approach that may be different and should be shared, if we are to follow the way for higher level of unification.

We look at the world from one point of a topological space, it has been say: what is the structure of this space? How is the knowledge of this structure related to the knowledge of reality? In this respect, any sounding of science is a way that moves us from one point to others in this space, with the perspective of producing enlarge modelling of our knowledge.