The Fundamentals of Imaging

From Particles to Galaxies

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The Fundamentals of Imaging

From Particles to Galaxies

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Preface

For highly developed living species, especially mankind, the creation of images is an important factor in their awareness of being alive and of consciousness — the understanding of one's identity and place in the world. Image formation is also an essential process in the advance of man's knowledge of the world and the Universe in which he lives. It is through images that we comprehend and interpret our surroundings and react to what happens in it. Aboriginal rock paintings in caves in Australia have been dated to more than 50,000 years ago and they are a testament to the importance that images have always had for mankind, even when living in primitive societies. When we sleep, and are in a state without consciousness, we dream and create images, often bizarre and unrealistic, that sometimes, but not always, can be recalled when we wake. In fairly recent times the interpretation of dreams was regarded by the psychoanalyst Sigmund Freud as an important tool in the treatment of psychiatric illness. Somewhat further back, the biblical story of Joseph (he of the multicoloured garment) hinged on his interpretation of the Egyptian Pharaoh's dreams in terms of an agricultural forecast for the years ahead.

The crudest type of imaging is just the determination that some object exists at a particular place without being able to discern its form in any way. This is usually referred to as *detection* rather than imaging and although it is a rather poor relation of detailed imaging it is of importance in many spheres of human activity — for example, in air traffic control or submarine detection. At the other end of the scale there are cases where the nature of an object is revealed by imaging in the very finest detail.

Of all the senses sight is king. There are the senses that require contact; we can taste what is in our mouths and we can touch what

we can reach. There is a party game in which an object is placed in a bag and just by feel alone one must try to identify what it is. Most people are quite successful at this for a simple object and can create a mental image of it. They are less successful for objects with a complicated structure — although blind individuals, whose sense of touch is far more sensitive and well developed, may do better. If the object is patterned in some way, e.g. it is a photograph, then no degree of sensitivity of touch could determine the full information that it offers to those viewing it directly.

Smell is a sense that has a limited range for humans but is more developed in some other species for which it has survival value, giving notice of the proximity of either prey or predator. Hearing for humans has a much larger range than smell and very loud noises, such as explosions due to major accidents or to artillery fire, can be heard over hundreds of kilometres. However, for sight the range is, to all intents and purposes, infinite. We may not be able to see the details and the exact form of a distant star or galaxy with the naked eye but if the intensity of light is sufficiently high then we can detect that it is there.

The first chapters of this book deal with the structure of the human eye, how it produces images and how it may have evolved. It cannot be guaranteed that the image of an object perceived by a viewer precisely represents its true form. If it is seen with the assistance of an optical system then there may be distortions introduced by that system; the eye itself is an optical system that can introduce distortion in a true image and, when this is troublesome, spectacles are used to reduce the distortion to an acceptable level. In other cases in which distorted or corrupted images have been formed, scientists have devised processes, referred to as image processing, mathematically based and implemented by computers, by which a better image can be obtained.

What we have been describing so far is either the everyday detailed viewing of objects, ranging from the finest print to a landscape or a distant cloud, or just the detection of a luminous object, such as a star. There are contexts, usually of a scientific nature, where it is required to observe objects so small that they cannot be resolved

by an unaided eye or, if very large, e.g. a galaxy, so distant that they can only be seen as point light sources, or even not at all, by the unaided eye. In such cases there are optical devices, microscopes and telescopes that enable a more-or-less true image of the object to be seen and recorded.

The implication in the above discussion is that the objects are being viewed, with or without instrumental aids, with visible light. However, there are many radiating objects which emit too little visible light to be seen directly but do emit other kinds of radiation that can reveal an image of their form and structure by the use of suitable instruments. In the field of astronomy the range of electromagnetic radiation used for detecting or imaging extends from radio waves with wavelengths a few tens of centimetres to γ -radiation with wavelengths of order 10^{-14} metres.

There is an important difference between seeing this book and seeing a candle flame. A candle flame, like a star, itself emits visible light so that there is no need for any other source of radiation to be used in order for it to be seen. However, a book emits no visible radiation so, to see this book, it is necessary first to illuminate it and then to recombine the radiation scattered from it to form an image. There is a general rule that when producing an image the resolution attainable is, at best, no better than the wavelength of the wave motion being used. If the object to be seen is very tiny and fine details of it are to be imaged then normal visible light may not give the resolution required and radiation of a shorter wavelength, e.g. ultraviolet light, may then be used.

There are many important categories of image formation that involve the recombination of a wave motion scattered by an object. Notice that I have used the words 'wave motion' here because the scattering need not be of light waves, or some other form of electromagnetic radiation, but could be of another kind. Images can be formed by the use of ultrasound — sound waves of very high frequency — and this has both medical and engineering applications. Indeed, it is by the use of ultrasound that bats, the flying mouse-like creatures, detect their prey, flying insects, at night. Electrons that, according to modern theory and as confirmed experimentally, can

have wave-like properties give another possible wave motion for imaging.

One of the great scientific achievements of the twentieth century is the development of methods of detecting the positions of atoms in crystals by the technique of x-ray crystallography — creating an image of a crystal structure. This has enabled important developments in many branches of science, no more so than in biochemistry and medicine for which knowledge of the crystal structures of proteins, of deoxyribonucleic acid (DNA) and other macromolecules has enabled enormous advances to be made. However, in this case there are no physical ways of combining the x-rays scattered by the crystal to form an image by any physical process; instead the pattern of scattered radiation must be handled mathematically and the image is the result of calculation. The great advances made by x-ray crystallography would have been impossible without the availability of powerful computers.

In this book we shall explore a wide range of techniques for detecting and imaging objects of various kinds, ranging in size from galaxies down to the fundamental sub-atomic particles of matter. There will also be brief descriptions and explanations of the objects being imaged; for example, before ways of imaging exotic particles are described in the final chapter there will be an explanation of what those particles are and how they relate to the physical world. We shall be describing how these various techniques can both be of benefit to mankind, for example, in medical imaging and by making flying in aircraft a safer activity, and also extend our knowledge of the Universe and all its contents. It will not be a formal, highly mathematical and comprehensive treatment but one that reveals the wide range of imaging techniques that are available. It should be accessible to those with an interest in science and who have studied science at school to an intermediate level.