Chapter 1

Introduction

1.1 What Is Structural Color?

In nature, a tremendous number of orders and patterns are generated spontaneously, which enliven our surroundings. One of the most remarkable consequences of these processes reveals itself as the so-called *structural color*, which exhibits striking brilliancy owing to elaborate structures furnished with living creatures. They sometimes reflect surprisingly intense light in a wide angular range, while in another case prohibit any reflection of light. These functions are natural consequences of complicated interactions between light and microstructures through purely physical properties of light.

The scientific definition of structural color has not yet been settled and its characteristics are often referred to in contrast to pigmentary color. When a matter is illuminated with white light, we see a specific color if the reflected light of only a particular wavelength range is visible to our eyes. There are two ways to eliminate the other wavelengths of light (see Fig. 1.1): One is the case where the light is absorbed in a material, which is usually the case for ordinary coloration mechanisms in colored materials such as pigments, dyes, and metals. In these materials, the illuminating light interacts with electrons within the material and excites them to higher excited states by virtue of energy consumption of light. The color in this case is anyway caused by the exchange of energies between light and electron.

The other is the case where the light is reflected, scattered, and deflected not to reach the eyes under the presence of a specific structure. The coloration in this case is based on a purely physical operation of light that interacts with various types of spatial inhomogeneity. Thus, it does not essentially lose the energy of light. In this sense, even a simple prism should

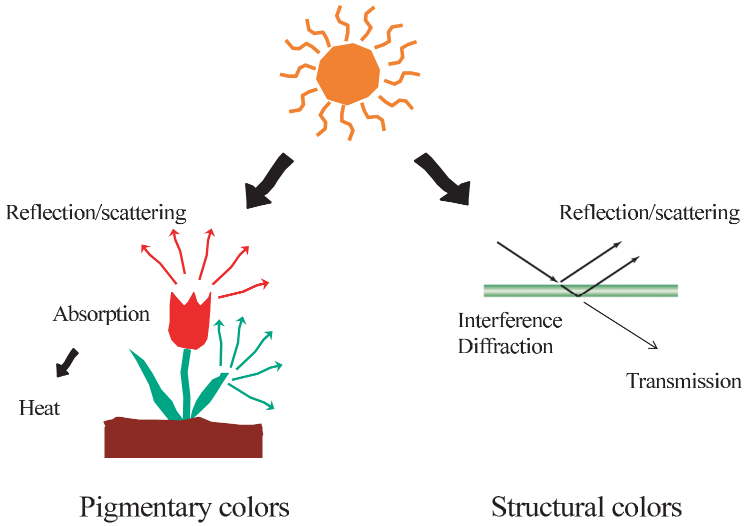

Fig. 1.1 Pigmentary colors and structural colors. (Illustrated by Dr. S. Yoshioka.)

be categorized into this type of structural color, because the light waves with different wavelengths are deflected differently by virtue of the dispersion of the refractive index. However, most of the structural colors appearing in nature somehow utilize special mechanisms to enhance the coloration. It is generally believed that the structural colors mostly come from the following five elementary optical processes and their combinations: (1) thin-film interference, (2) multilayer interference, (3) diffraction grating, (4) light scattering, and (5) photonic crystal.

Structural color and *iridescence* are two major keywords for these phenomena and seem to be used commonly in an equivalent sense. However, in relation to the above optical processes, the iridescence should be used somewhat in a restricted sense when the color apparently changes with viewing angles. For example, thin-film interference is generally iridescent, while light scattering is usually non-iridescent but of a structural origin.

Although many excellent books (Simon, 1971; Fox, 1976; Nassau, 2001; Parker, 2003; Kinoshita, 2005; Berthier, 2007) and review articles (Parker *et al.*, 1998b; Srinivasarao, 1999; Parker, 2000; Vukusic and Sambles, 2003; Parker, 2004; Kinoshita and Yoshioka, 2005b; Kinoshita *et al.*, 2008) have appeared so far, the field of structural colors is rapidly growing year by year so that new mechanisms and species appear almost every year. Thus, new information is always expected. Further, the above articles tend to classify the structural colors through their mechanisms and take some species as the typical examples. Thus, to overview the whole species-specific fields through an eye of "structural color" is quite difficult. In the present book, I dare to summarize the world of structural colors on the basis of species and not of the mechanisms. This clearly benefits us to treat them even when their mechanisms are not completely known or only partly known. It is also possible to describe the whole story for each species under species-specific background.

This book is organized as follows: In Sec. 1.2, we will describe the historical review of the structural colors that began with the observations by Hooke and Newton in the 17th century, which was then succeeded by Lord Rayleigh and Michelson, and flourishes nowadays in various scientific and industrial fields. In Chap. 2, a brief description of structure-based properties of light has been given, which will appear later as actual forms in various living creatures after a variety of modifications (Kinoshita and Yoshioka, 2005b, 2005c; Kinoshita *et al.*, 2008). In Chap. 4, we will show the structural colors in lepidopterans, with a particular emphasis laid on the famous *Morpho* butterflies. In Chaps. 5–8, we demonstrate the structural colors appeared as specific forms in beetles, birds, fishes, plants, and the other animals. In Chap. 9, we prepare the detailed derivations of the important formulas, which would be of help to the readers to study the physical mechanisms.

1.2 Historical Review

The study of structural colors has a long history. Probably, the oldest scientific description on the structural colors appeared in "*Micrographia*", written by Hooke (1665). In this book, he described the microscopic observation of the brilliant feathers of peacock and duck, and found that their colors were destroyed by a drop of water. He speculated that alternate layers of thin plate and air might strongly reflect the light. Newton (1704) described in "*Opticks*" that the colors of the iridescent peacock arose from the thinness of the transparent part of the feathers. In spite of these pioneering works on structural colors, further scientific development must have waited for the establishment of electromagnetic theory by Maxwell in 1873 and also for the experimental study on the electromagnetic wave by Hertz in 1884. The fundamental properties of light such as reflection, refraction, interference, and diffraction could be quantitatively treated thereafter, and the studies on structural colors proceeded quite rapidly.

However, there arose a significant conflict between two hypotheses: One was *surface-color*, which was proposed by Walter in 1895 (see Rayleigh (1919)) and was thought to originate from the reflection at a surface involving pigments. The other was *structure-color* that originated from purely physical operation of light. These two hypotheses drove the world of physics into two at that time. Walter explained the variation of colors with the incident angle of light as due to the change of polarization in the reflection at the absorption band edge. The idea of surface-color was then succeeded by Michelson (1911), who conducted the experiments of the reflectivity on seemingly metallic samples such as golden scarab beetle and *Morpho* butterfly, and described that they resembled the surface reflection from a very thin surface layer involving dye.

Lord Rayleigh, on the other hand, derived a formula to express the reflection properties from a regularly stratified medium using electromagnetic theory (Rayleigh, 1917), and considered it as the origin of colors of twin crystals, old decomposed glass and probably those of some beetles and butterflies. He surveyed the studies performed so far, and described that the brilliant colors, which varied greatly with the incident angle of light, were not due to the ordinary operation of dyes, but came from the structural colors (Rayleigh, 1919).

Many experimental works were performed, on an optical microscopic level, to clarify the relationship between brilliant colorations and the microstructures at the surface of iridescent, metallic, and whitish materials. Onslow (1923) observed more than 50 iridescent animals to settle the conflict between these hypotheses. Merritt (1925) measured the reflection spectra of tempered steel and *Morpho* butterfly, and interpreted in terms of thin-layer interference. In 1924–1927, Mason (1923a, 1923b, 1926, 1927a, 1927b) published a series of papers on various types of color-producing structures in animals investigated by a microscope and supported the interference theory. Thus, the interference of light enforced the power gradually, which finally kept away the interest of physicists.

The complete understanding of their structures was made after the invention of electron microscope. In 1939, the first attempt was made to clarify the mechanism of blue coloring in the bird feathers. Frank and Ruska applied the first marketable electron microscope, which developed in this year, and found spongy structure consisting of keratin and air at the inner wall of the medullary cell of blue feather of a bird pitta (Frank and Ruska, 1939; Frank, 1939). In 1942, Anderson and Richards (1942) and Gentil (1942) investigated the scales of the famous *Morpho* butterflies.

These observations revealed a surprisingly complicated structure on a tiny scale of the butterfly wing, which accelerated the structural study on a nanometer scale. Many biologists attempted to elucidate the structures causing iridescence and accumulated enormous data. In 1960, a sophisticated microstructure was reported on the feather of a humming bird (Greenewalt *et al.*, 1960a). After then, beautiful microstructures were discovered one after another in many species of birds such as peacock, humming bird, pheasant, and dove. In 1967, the structural coloration due to helicoidal structure analogous to the cholesteric liquid crystal was found in scarabaeid beetles (Neville and Caveney, 1969). Beautiful multilayered structure was found in a kind of a jewel beetle in 1972 (Durrer and Villiger, 1972). Highly reflecting structures were found in the 1960s within the integuments and eyes of fish and cephalopods, which are now known as animal reflectors (Land, 1972). On the other hand, regular modification of the surface was discovered to cause the anti-reflection effect, which is well known as moth-eye structure (Bernhard *et al.*, 1968). The motile nature of the iridescent cell in fish to the ambient illumination was clarified in 1982, which was due to a change in the distance between adjacent regularly arranged platelets (Lythgoe and Shand, 1982).

On the other hand, the developmental studies concerning the formation of such microstructures are quite limited even up to now. Good examples for these studies are those in butterfly scale and multilayered structure in beetle. Ghiradella reported a comprehensive study on the formation process of butterfly microstructures within a scale-forming cell using an electron microscope (Ghiradella *et al.*, 1972; Ghiradella, 1989, 1998). Schultz and Rankin (1985b) reported the development of multilayer structure before and after ecdysis of beetle.

In spite of the progress of the structural studies in biology, the physical interpretation of structural colors had not essentially proceeded, since Lord Rayleigh proposed the multilayer interference. Only recently, the structural colors have been a subject of extensive studies because their applications have been rapidly growing in many industrial fields related to vision such as painting, automobile, cosmetics, display, and textile. It has been soon noticed that simple multilayer interference no longer reproduces the actual appearance of the natural color. Furthermore, recent researches have revealed that even a very simple structure in nature has surprising multiple functions, which by far exceed our expectations. In the following chapters, we will show the beautiful microstructures produced in the natural world and will give a physical basis for their optical operations.