Rendering of 'Play of Color' using Stratified Model based on Amorphous Structure of Opal

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Abstract. This paper focuses on modeling and rendering of structural color in computer graphics. Structural color is derived from microstructure of an object, which causes various optical phenomena, such as reflection, refraction, diffraction, interference, and so on. In this paper, the authors take 'play of color' of opal as a typical and complex phenomenon of structural colors and propose modeling and rendering methods suitable for the phenomenon. Result images reveal that the proposed methods are capable of representing 'play of color' of opals and have possibility to extend to general structural color rendering.

1 Introduction

Increase of computing power can generate computer graphics with high reality[1][2]. To render real scenes, color of objects is one of the key issues to be modeled appropriately.

Various colors are found through the nature world and these colors can be divided into two classes based on mechanisms of coloring. One is derived from dyes, the other is from structure of objects.

In general, colors from dyes are modeled as the relationship of incoming and outgoing lights on a surface of an object. These approximate models have been obtaining excellect results.

On the other hand, colors from structures of objects, called structural colors, are not easy to be modeled, because structural color shows drastic change depending on wavelength, viewpoint and positions of light sources. These complex behaviors are caused by an optical phenomenon which is derived from microscopic structure of an object. Some examples that have structural colors are shown in figure 1. There objects have the regular structure on their surfaces that brings reflection, refraction, diffraction and interference of an incoming light. Therefore, to reproduce structural colors, the model which involves a microstructure of an object is suitable.

In this paper, the authors take 'play of color' of opals as the typical and complex phenomenon of structural colors and propose the modeling and rendering methods suitable for the phenomenon.
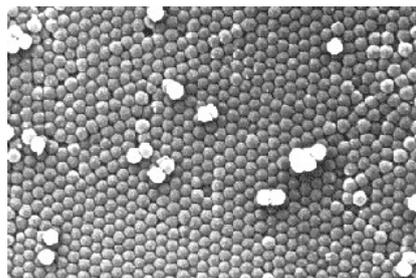
Fig. 1. Examples of Structural Color

Fig. 2. Microstructure of Opal under SEM[4]

2 Opal Model

2.1 Structure of Opal and 'Play of Color'

Opal is silica (silicon dioxide, SiO_2) mineral extensively used as a gemstone[3]. The structure of opal is regular lattice in microscopic. However, because usual opal contains cracks, the macroscopic structure is irregular like amorphous. The microscopic structure of opal, which is acquired using scanning electron microscope(SEM), is shown in figure 2.

Opal shows different colors with the change of viewpoint, orientation of itself or lighting condition. This phenomenon, called 'play of color', is considered as the result of various optical phenomena derived from the structure of opal. The change of colors with moving a light source is shown in figure 3.

2.2 Proposed Model

Foregoing researches for reproducing structural colors are focused on microscopic structure[5]. However, complex behavior of 'play of color' is mainly caused by the irregular structure on macroscopic scale. Therefore, to reproduce the structural

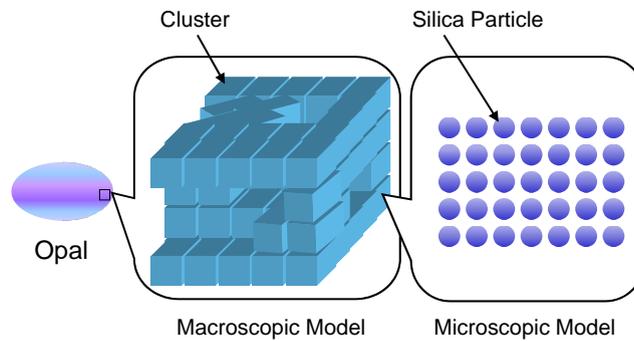**Fig. 3.** 'Play of Color' Phenomenon of Opal

Fig. 4. Proposed Model of Opal

color of opal, considering of only microscopic model and optical phenomena, is insufficient.

In the proposed model, the complex structure of opal is represented as combination of models in two different scale. The regular structure on microscopic scale is modeled as the 'cluster' of silica particles. The optical behavior of cluster is calculated based on the order of silica particles. On the other hand, the irregular structure on macroscopic scale is represented as arrangement of clusters and voids. Each cluster has its own orientations, which has correlation with orientations of neighboring clusters . The ratio of clusters to voids is decided based on the average void ratio of real opal.

2.3   Microscopic Modeling: Particle Arrangement in Cluster

In a cluster, silica particles are ordered as face centered cube. All clusters are assumed to have the same particle size and lattice distancem, therefore, same reflectance property. This assumption is useful to reduce computing time.

2.4   Macroscopic Modeling: Arrangement of Clusters and Voids

The irregular arrangement of clusters and voids is decided procedually. The procedure is as follows:

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1. Divide whole opal shape into regular cells. Each cell contains either cluster or void.
2. Initialize all cells as void.
3. Select one cell randomly.
4. Set the selected cell and its neighboring cells as cluster. The orientation of these clusters are average orientation of neighboring clusters already set. The size of neighborhood is decided under the following exponential probability distribution function.

$$P(r) \propto \ e^{-\frac{r}{R}} \tag{1}$$

5. Repeat step 3 to 4 until the ratio of void becomes below the average void ratio of real opal.

3   Rendering

Optical phenomena, such as reflection, refraction, diffraction and interference, play important roles to emerge 'play of color'. These properties differs depending on wavelength of light. Therefore, to render 'play of color', the authors adopt multi-channel ray tracing method, which uses rays of multiple wavelength.

In ordinary ray traching method, rays are traced from viewpoint to light sources. In ordinary, a diffuse component of reflection is decided by positional relationship between reflecting point and light source with assumption that intensity of light is same in everywhere and checking whether the point is lit or not is enough to render scenes properly. However, in this model, each cluster has different lighting condition because of the complexity of structure.

To reproduce the difference of incoming light for each cluster, ray tracing from light sources is used together[6]. In ray trace from light sources, incoming intensity of light is calculated based on the arrangement of clusters and microscopic reflectance properties and is stored for each cluster. To render the image from viewpoint, the rays are traced from viewpoint and the intensity of light is calculated based on the arrangement of clusters and incoming light stored already. The intensity is calculated for each wavelength, then, using color matching function, the distribution of light intensity is translated to RGB values. Figure 5 shows the whole procedure of rendering.

3.1   Calculation of Reflectance

Before tracing of rays, optical properties of a cluster must be calculated and stored in tables.

The direction of an incoming light relative to normal vector of a surface of a cluster is represented as polar coordinates. For each direction, the intensity of reflection light, the direction and intensity of refraction light, and the diffusion on a surface are calculated. The ratios of these outgoing lights are decided with assumption that the layered structure of silica particles causes diffraction and interference of incoming lights.
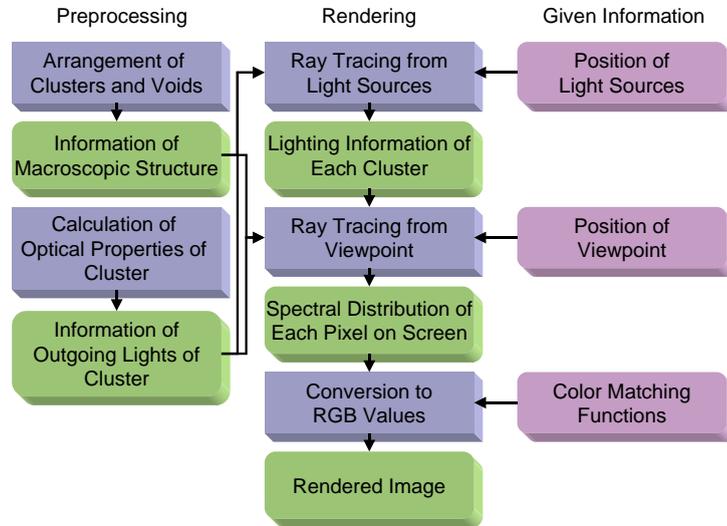
Fig. 5. Flowchart of Processing

3.2 Ray Tracing from Light Sources

The procedure of tracing is shown in figure 6. At a surface of a crossing cluster, the incoming light is divided into specular reflectance light and permeation light. The intensity of specular reflectance light is changed because of diffraction, so the attenuation of light is calculated based on the optical property of a cluster calculated previously. Each cluster stores the intensity and direction of crossing light. This process is repeated until the intensity of light becomes small enough to neglect it.

3.3 Ray Tracing from Viewpoint

The procedure of tracing from viewpoint is shown in figure 7. Rays are traced from viewpoint. At the crossing point of a cluster, the reflectance intensity is calculated based on the stored information of specular and diffusion light intensity of each cluster. Phong model is adopted for calculation of diffusion. The intensity I is:

$$I = \sum I_{kd} \cos \theta + \sum I_{sp} \cos^n \theta'$$

(2)

where I_{kd} and I_{sp} are intensities of diffuse and specular light, θ is the angle between diffuse light and a cluster surface, and θ' is the angle between specular light and a viewing vector.
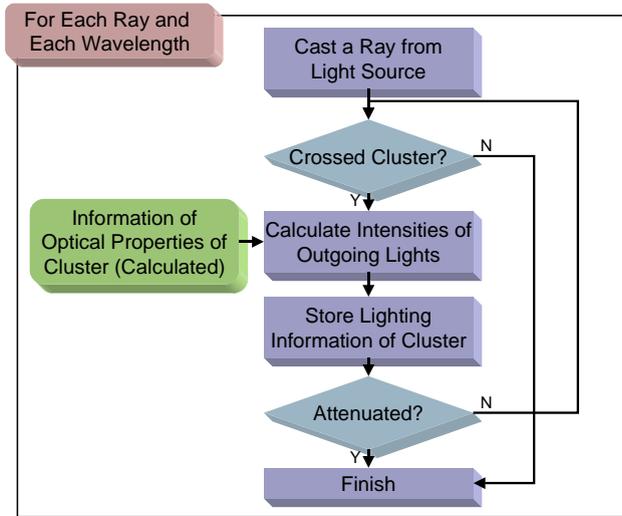
Fig. 6. Flowchart of Ray Tracing from Light Sources
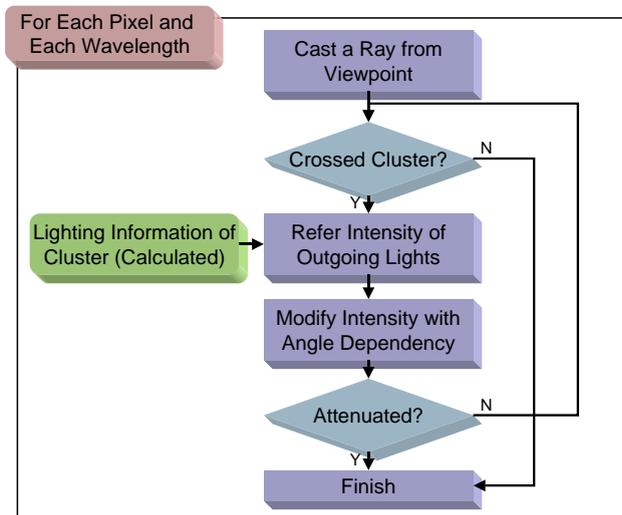

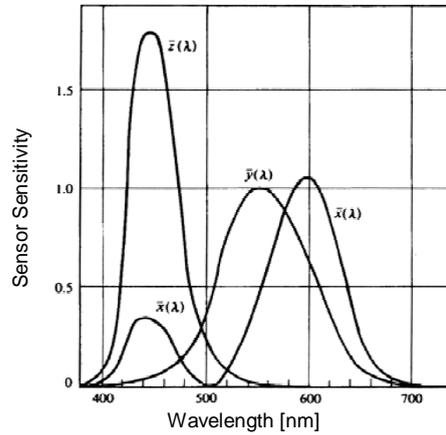**Fig. 7.** Flowchart of Ray Tracing from Viewpoint

Fig. 8. Color Matching Function of XYZ Color Space

3.4 Conversion to RGB Color Image

To acquire an RGB image, first, a color matching function of XYZ color space (figure 8) is used to get XYZ values of each rendered pixel. For conversion from XYZ color space to RGB color space, the following equation is used.

$$\left. \begin{array}{l} R = 1.910X - 0.532Y - 0.288Z \\ G = -0.985X + 1.999Y - 0.028Z \\ B = 0.058X - 0.118Y + 0.898Z \end{array} \right\} \tag{3}$$

4 Result

4.1 Computing Environment

The computing environment to make a model of an opal and to render is as follows:

- CPU: PentiumIII 800MHz
- Memory: 512MB
- OS: FreeBSD 4.2

All programs are written in C and C++.

4.2 Arrangement of Cluster

The shape of an opal is modeled as an ellipsoid. The ellipsoid is divided into regular cells, the division numbers along each axis are 100, 75 and 25. The average
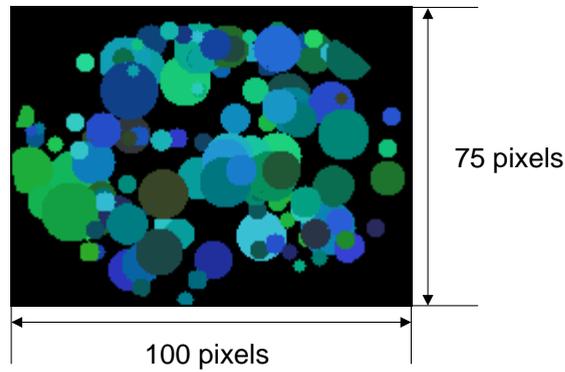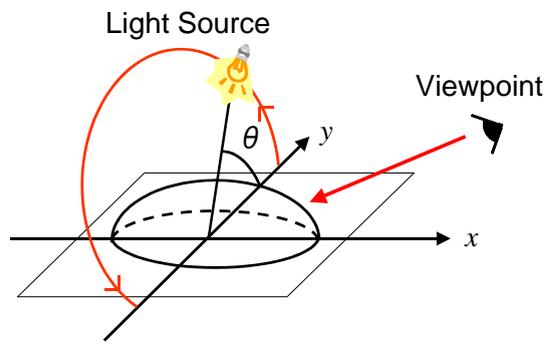
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Fig. 9. Result of Cluster Arrangement

Fig. 10. Viewpoint

size of neighborhood is 6. Result of the arrangement is shown in figure 9. This picture shows of the result on plane z=0, and RGB value of each pixel represents the orientation of a cluster in the manner that R, G, B correspond to X, Y, Z component of orientation.

4.3   Rendered Images

Arrangement of an opal, a light source and a viewpoint is shown in figure 10. The angle θ between viewing vector and light-to-opal vector is changed from -60 degree to 60 degree. The rendered images are shown in figure 11.

5   Discussions

Various colors were seen on a surface of the rendered opal and these colors changed as the arrangement of light source, viewpoint and opal changed. These
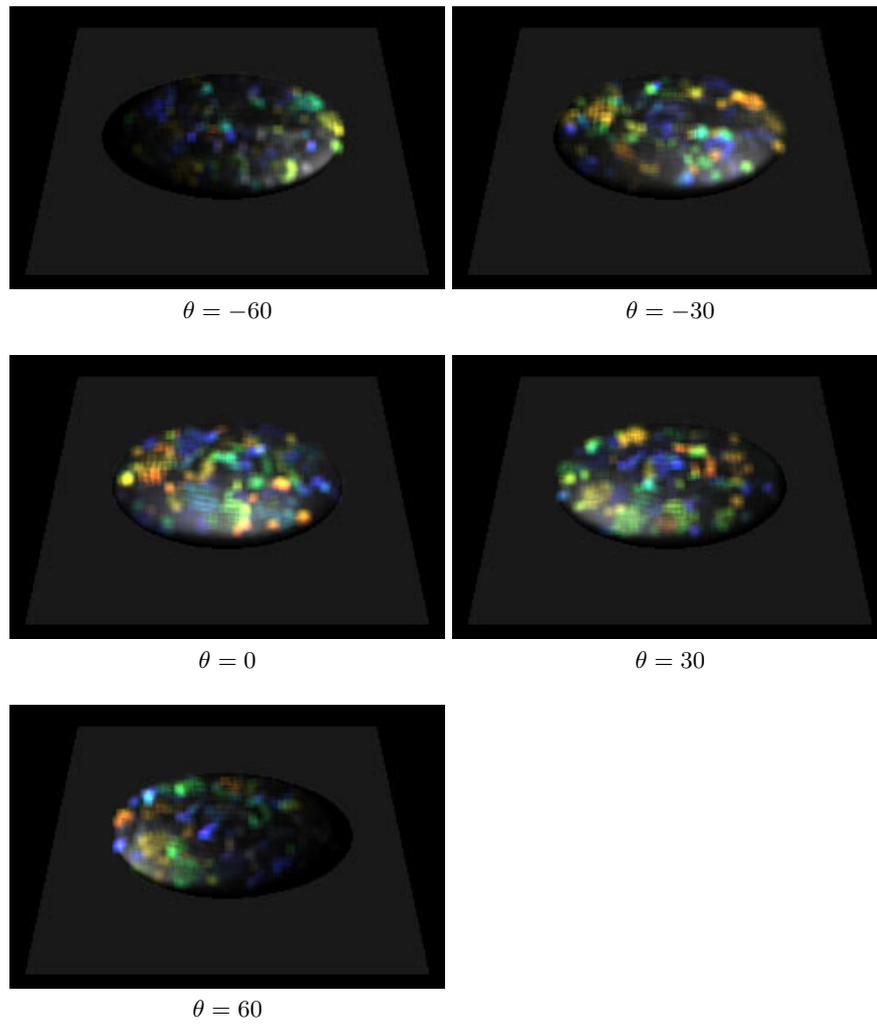
$\theta = -60$ $\theta = -30$

$\theta = 0$ $\theta = 30$

$\theta = 60$

Fig. 11. Rendered Images

two features of rendered images proved that the proposed model and rendering method are capable to representing 'play of color' of opal.

To acquire one image, computing time was about one hour. The whole consumed time breaks down into three parts: the structure arrangement took about 10 minutes, ray tracing from light sources about 30 minutes, and ray tracing from viewpoint about 20 minutes. To acquire an image from another viewpoint, only ray tracing from viewpoint is needed and ray tracing is suitable for pallelization. Therefore, this computing time left much to be reduced.

Although the proposed model can reproduce generic appearance of opal, colors and their change cannot be controlled by user, so reproduction of a real specific opal is difficult. To control of detailed properties of rendered images, the authors consider that more information and measurement about structure of real opal are required.

6   Conclusions

In this paper, the authors proposed the modeling and rendering methods to reproduce 'play of color' of opal, which is a typical and complex phenomena of structural color. To reflect the structure of opal, which is regular in microscopic but irregular in macroscopic, the proposed model consisted of two scales. For the representation of optical phenomena depended on wavelength of incoming light deeply, multi-channel ray tracing from not only viewpoint but also light sources were adopted. The rendered images were shown that the proposed methods are capable of representing 'play of color' of opal. Since 'play of color' of opal includes most of all elements of structural colors, the authors considered that the proposed method can be applicable for modeling of other objects which show structural colors.

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