

## COMPUTATIONAL APPROACH FOR DETERMINING THE DIRECTIONALITY OF LIGHT: DIRECTIONAL-TO-DIFFUSE RATIO

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### ABSTRACT

The directionality of light is defined as the balance between the diffuse and directional components of light within an environment. It is an indicator about the spatial distribution of light flow onto an element or into a space. This paper presents a new luminance based metric that quantifies the directionality of light. The diffuse and directional components of the luminous environment are isolated as a unique feature of simulation-based approach. The rationale and methodology of the directional-to-diffuse ratio is discussed through visual demonstrations and quantified metrics.

### KEYWORDS

Directionality of light, light flow, directional-to-diffuse ratio, lighting metric.

### INTRODUCTION

Architectural lighting analysis is dominated by the investigations of six broad matters: (i) quantity of light, (ii) spatial distribution of light, (iii) directionality of light, (iv) glare, (v) spectral content of light, and (vi) energy efficiency. This paper introduces a novel metric for assessing the directional character of light.

Directionality of light is the balance between the diffuse and directional components within an environment. It has a significant impact on the appearance of 3D objects; and the visual performance and comfort of occupants within that environment. Poor directionality may produce harsh shadows on the task, cause veiling reflections towards the viewing angle, or create a dull environment. Adequate directionality may model 3D surfaces, reveal the surface textures or details of a task, and create an aesthetically pleasing environment (CIE, 1986). Although the directional nature of lighting is significant in achieving the intended visual effect, performance, and comfort, measuring and quantifying it has been a challenge.

There are a number of illuminance based performance indicators that are used for determining the directionality of light. They include mean

cylindrical and semi-cylindrical illuminance, scalar (mean spherical) illuminance and semi-scalar (mean hemispherical) illuminance, vector illuminance, vector-to-scalar illuminance ratio, and cubic illumination (Cuttle 1971, Cuttle 1997, Cuttle, 2003a, Cuttle 2003b, Lynes et.al. 1996, Ashdown 1998). Others have evaluated directionality based on the visual appearance of 3D objects (Frandsen 1987, Madsen and Donn, 2006).

The directionality metric described here, is based on luminance values, rather than illuminance. Luminance is defined as the luminous intensity leaving, passing through, or arriving at a surface per unit area in a given direction (IESNA, 1999).

Lighting patterns on any object are determined by three factors: (i) directionality of light, (ii) geometric and surface properties of the object being viewed, and (iii) viewing angle (Cuttle 1971). A luminance based metric incorporates all of these three factors and thoroughly describes the scene as perceived by the human visual system. Although previous studies do not evaluate directionality through a luminance based metric, it is important to note that the effect of directionality of lighting has been implicitly addressed through its impact on visual comfort and performance. Comfort and performance metrics such as luminance contrast, contrast rendering factor, and glare are all luminance based performance indicators.

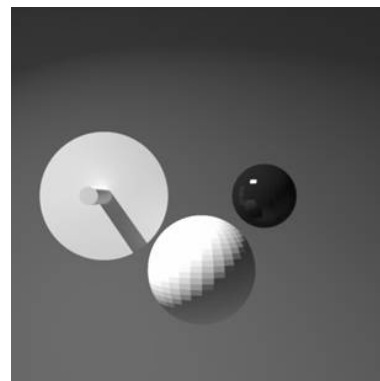


Figure 1 Shadow pattern (peg on a disk), shading pattern (matt white sphere) and highlight pattern (black glossy sphere)

## DIRECTIONALITY OF LIGHT

Cuttle (1971, 2003a) has shown that directional effects of light on 3D objects within a light field (i.e. under similar lighting conditions) can be categorized in three distinct patterns: (i) the shadow pattern, (ii) the shading pattern, and (iii) the highlight pattern. These patterns are demonstrated through three physical objects (which will be referred as the directionality set, hereafter): A peg on a disk reveals a shadow pattern, as the peg casts a shadow on the disk. A matt white sphere reveals a shading pattern, caused by the variation of light flow on a convex surface. A glossy black sphere reveals the reflected highlights. Cuttle's directionality set emphasizes that observer's view angle, geometric and material properties of the objects are as important as the directional characteristics of light for rendering the appearance of 3D objects.

The three objects (thus three lighting patterns) have been recreated in a virtual environment with similar geometry and representation of the physical materials (Figure 1). Radiance Lighting Simulation and Rendering system (LBNL) is used to generate the virtual counterparts of Cuttle's physical objects. The directionality of light is simulated through physically based modeling of light sources: Electric lighting is simulated through luminaire geometry, luminous flux, color information, and candlepower distribution. Daylighting is defined through accurate position of the sun and application of the CIE Clear Sky model. Geometric and surface properties of the object have been defined through appropriate 3D modeling techniques and physically based definitions of

reflection properties. Viewing angle is determined by the camera position and viewing direction.

## DIRECTIONAL-TO-DIFFUSE RATIO

A new metric is derived from the basic definition of directionality: The diffuse and directional components of the luminous environment are isolated as a unique feature of simulation-based approach and the ratio of the directional-to-diffuse light is calculated.

Through multi-pass simulations and image subtraction methods, diffuse and directional lighting components are identified (Figure 2). The directional components include the direct light from light sources and specular reflections within the environment, which refer to all non-Lambertian reflections and transmissions (including refraction, ideal reflection and directional scatterings). The diffuse reflections refer to the Lambertian components from all surfaces other than the light sources (Ward and Shakespeare, 1997).

Figure 3 illustrates the separation of directional and diffuse components in an electric lit environment. The first image includes the directional (direct light from light sources and specular reflections from the environment) and diffuse components (interreflections) of the luminous environment. In the second image, the diffuse component is removed. The subtraction of the second image from the first one produces the third image, which is the resultant of the diffuse interreflections within the interior space.

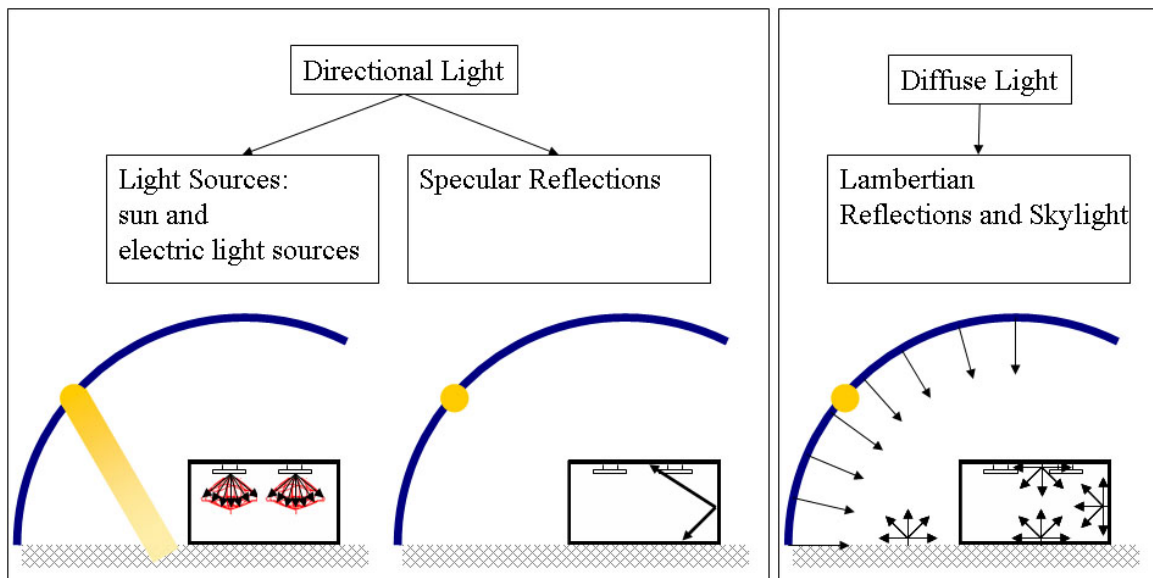
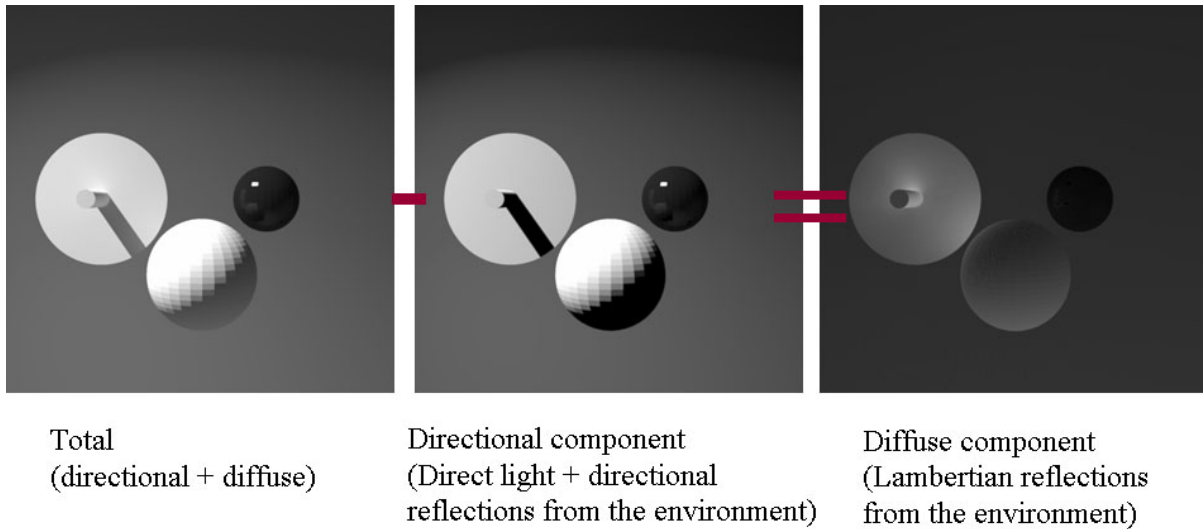


Figure 2 Directional and diffuse components of light



Total  
(directional + diffuse)

Directional component  
(Direct light + directional  
reflections from the environment)

Diffuse component  
(Lambertian reflections  
from the environment)

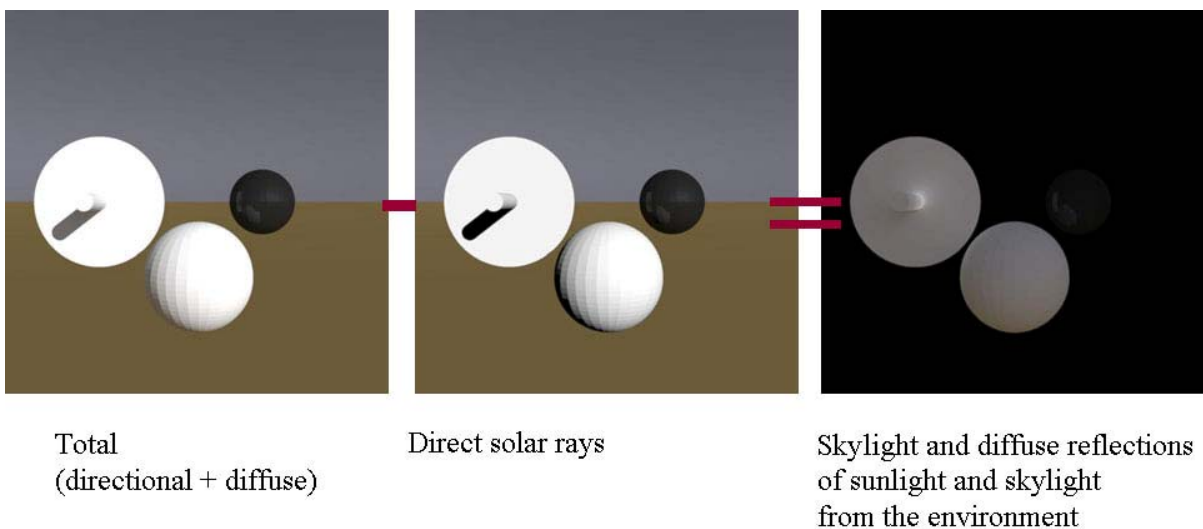
Figure 3 Image subtraction method is used to isolate the directional and diffuse components of lighting

Figure 4 demonstrates the same concept with daylighting. Direct solar rays form the directional component. The diffuse component includes the skylight and the diffuse reflection of solar radiation and skylight from surfaces. It is important to note that in daylit interior environments, the skylight from the windows should be isolated through another simulation pass and be included in the directional component. Although skylight is diffuse in nature, skylight entering an interior space from an aperture has a directional character.

The ratio of the directional and diffuse components is calculated with average luminance values on particular objects. In physically based rendering, RGB values are calculated through radiance values in three channels, which represent the intensity

reflected from a surface towards each pixel in the viewing direction. In a high dynamic range image format (Radiance RGBE, hdr), RGB values can be transformed to absolute CIE XYZ values, and CIE Y equals to luminance in  $cd/m^2$ . As a result, directional-to-diffuse luminance ratio can be quantified on a pixel scale to evaluate the directional strength of the light flow onto an element or into a space. For practical reasons, it is expressed as the percentage of the directional component of light in the rest of the paper:

$$Directionality(\%) = \frac{DirectionalLight * 100}{(Directional + DiffuseLight)}$$



Total  
(directional + diffuse)

Direct solar rays

Skylight and diffuse reflections  
of sunlight and skylight  
from the environment

Figure 4 Separation of the directional and diffuse components of daylighting

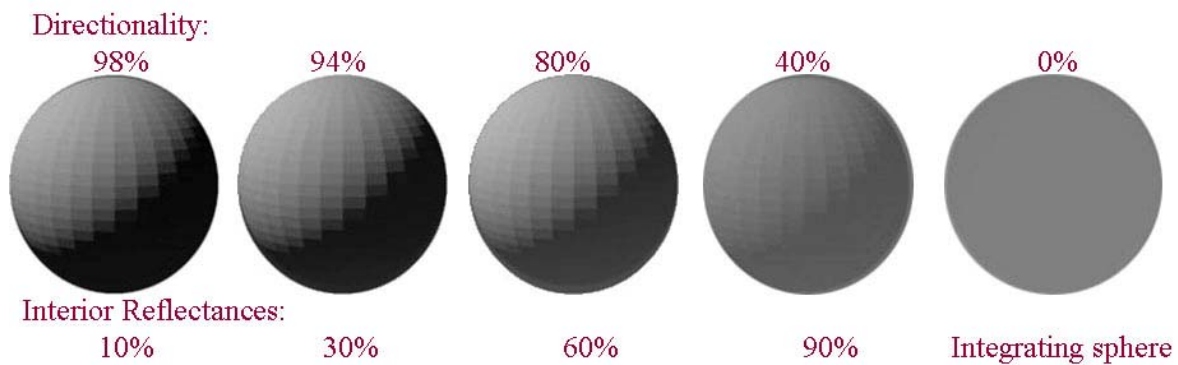
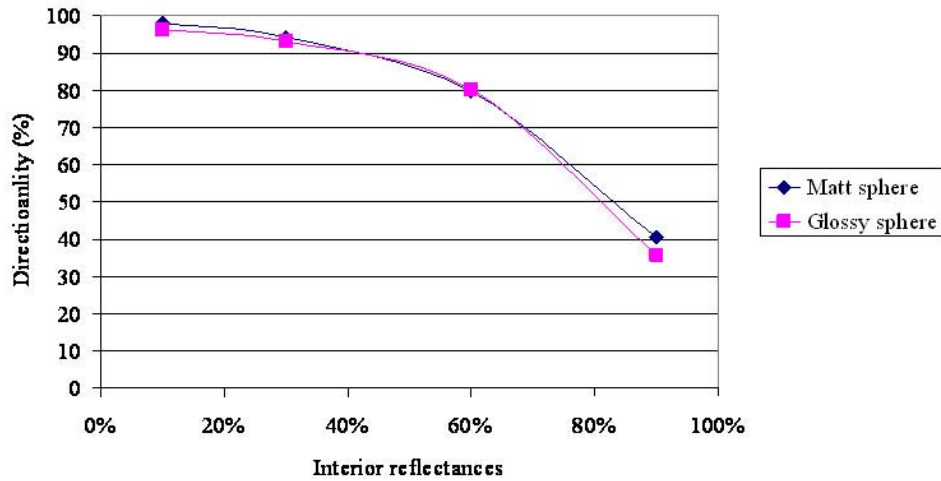


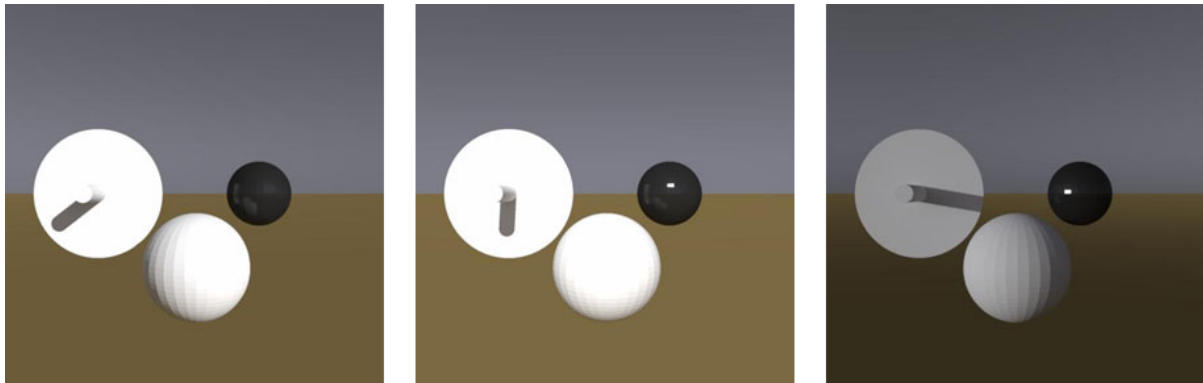
Figure 5 Directional-to-diffuse ratio for the objects under single point light source as the internal reflectances are varied (a. 10%, b. 30%, c. 60%, d. 90%) to enable varying diffuse component within an enclosed space. The visual appearance of the white matt sphere is provided along with the quantified directional-to-diffuse ratio. The fifth image (e) demonstrates the matt sphere in a virtual integrating sphere.

A series of simulations have been performed to demonstrate the effectiveness of the metric. In the first series, the directionality set is simulated in an indoor space, illuminated with a single electric light source coming from top left. The reflectance of the interior surfaces have been varied from 10% to 30%, 60%, and 90%. The interior with 10% reflectance has minimal interreflections and directional light is dominant in the environment. As a result, strong directionality creates harsh shadows and shading patterns. The interior with 90% reflectance creates a luminous environment, where diffuse lighting is dominant and it creates a relatively uniform and dull environment.

The outcome of the directional-to-diffuse ratio can be best appreciated when it is viewed side by side with the visual information. Figure 5 demonstrates the ratio for the same environment with four different interior wall reflectances. The ratios are given both for the matt surface and glossy sphere. The metric takes into account of the material properties of each 3D object; thus provides an indicator for each object as viewed from a given viewpoint. The visual appearance of the white matt sphere is shown in the figure as a close-up view. Low interior reflectances

accentuate the directionality of light, which create dramatic variations across the sphere. High interior reflectances create a relatively non-directional lighting conditions, which hampers the perception of the object attributes. The last image shows the object within a virtual integrating sphere; i.e. under uniform lighting conditions. The object completely loses its 3D character and appears flat.

The second series of simulations have been performed with the directionality set under daylight in different times of a day (Figure 6). The variant in this set is the position of the directional light source; i.e. the sun. The sky and the ground form the diffuse lighting components. The shadows formed by the peg on the disk reveal the sharpness of solar radiation, especially in Figures 6a and 6b. Highlights are function of the geometry of the light source, glossy object, and the viewing angle. Therefore, highlights are present in the glossy sphere at certain times (Figure 6b and 6c) based on the position of the sun. The directionality metric responds to these highlights with increased numbers. The directionality percentage on the white matt sphere also captures the decreased level of sharpness of the setting sun with lower values (Figure 6c).



Glossy sphere: 84%  
 Matt sphere: 84%

Glossy sphere: 90%  
 Matt sphere: 85%

Glossy sphere: 92%  
 Matt sphere: 70%

Figure 6 Directional-to-diffuse ratio for the glossy and matt sphere in different times of the day

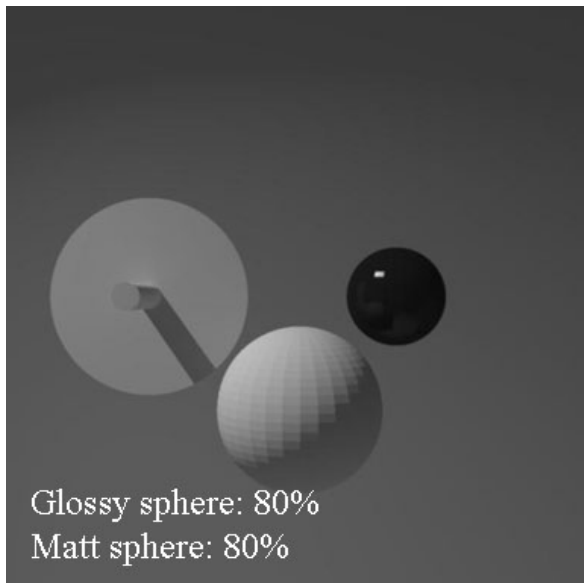
The third series of simulations demonstrate an interior setting with multiple point light sources. The peg on the disk reveals three shadows in response to three point sources placed at the top, left, and right positions in relation to the directionality set. The glossy sphere captures highlights from all three sources. Both the matt and glossy sphere captures the increased directionality with increased directionality percentages as a response to three light sources (Figure 7).

**APPLICATIONS**

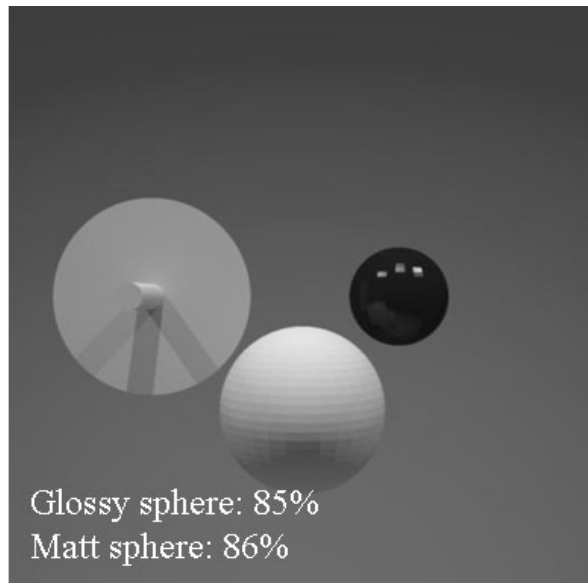
Applications of the directional-to-diffuse lighting ratio are manifold. In museums and art galleries, the metric can be used to study the effect of

alternative lighting designs on various object appearances.

Figure 8 demonstrates the sculpture of Venus di Milo rendered under four different lighting conditions. In the first two images, the sculpture is situated in an interior setting and lit by a spot light coming from two different positions. In the third image, the sculpture is rendered under daylight. In the fourth image, the sculpture is lit with lighting conditions that is captured in a physical setting using a High Dynamic Range (HDR) image technique. Note that the material properties of the sculpture remains the same in all renderings, and the variant is the directional character of light among four images.



Glossy sphere: 80%  
 Matt sphere: 80%



Glossy sphere: 85%  
 Matt sphere: 86%

Figure 7 Directionality set with single and multiple point source lighting





Figure 8 Venus di Milo under four different lighting conditions

The same metric can be used to assess the visibility of visual tasks that may include visual display terminals, 2D objects (such as paper) and 3D objects with any geometric and material properties. Therefore, it also provides valuable information about the lighting quality and quantity in offices, educational facilities and industrial settings. Examples given here are not exhaustive in nature. They are provided to highlight the application capabilities of the directional-to-diffuse ratio.

## CONCLUSION

Visual inspection of the renderings provide useful information about the appearance of a space or an object. There are many visual details in the luminous environment that cannot be expressed through numerical information. However, due to the restricted capabilities of the display devices, it may be impossible to evaluate the quantity and quality of the architectural lighting only through the appearance of a displayed image.

The paper demonstrates a proof of concept for a new directionality metric. Multi pass simulation techniques are used to split the directional and diffuse components of light within a luminous environment. Obviously, this is not feasible to achieve in a physical environment. Directional-to-diffuse ratio is demonstrated through numerical results and corresponding visual appearances.

Future work involves the utilization of the metric under diverse lighting conditions and environments

to develop general guidelines for different applications.

## REFERENCES

- Ashdown I. 1998. "The Virtual Photometer: Modeling the Flow of Light", Ledalite Architectural Products Inc, White Paper.
- CIE. 1986. Guide on Interior Lighting, 2. Ed., Publication 29.2, Vienna: Central Bureau de la CIE, 1986.
- Cuttle C. 1971. "Lighting patterns and the flow of light". *Lighting research and Technology*. 3(3), 171-189.
- Cuttle C. 1997. "Cubic Illumination". *Lighting Research and Technology*. 29(1), 1-14.
- Cuttle C. 2003a. *Lighting by Design*, Oxford: Architectural Press, 2003.
- Cuttle, C. 2003b. "An Integrated System of Photometry, Predictive Calculation and Visualization of the Shading Patterns Generated by Three-Dimensional Objects in a Light Field", *Proceedings of the CIE 2003 Conference*, San Diego, USA.
- Frandsen S. 1987. "The scale of Light". *International Lighting Review*. 1987/3, 108-112.
- IESNA. 1999. *Lighting Handbook Reference & Application*. Illuminating Engineering Society of North America, Rea, M., (Ed.).

LBNL. Radiance Lighting Simulation and Rendering system.

<http://radsite.lbl.gov/radiance/HOME.html>.

Lynes JA, W Burt, GK Jackson, and C Cuttle. 1996 "The Flow of Light into Buildings", Transactions of IESGB, 31(3), 65-91.

Madsen M and M Donn. 2006. "Experiments with a digital 'light-flow-meter' in daylight art museum e-buildings". 5th International Radiance Scientific Workshop, Leicester, UK.

Ward G and R Shakespeare. 1997. Rendering with Radiance, San Francisco: Morgan Kaufman Publishers.