APPLICATION OF THE STATE-OF-THE-ART COMPUTER SIMULATION AND VISUALIZATION IN ARCHITECTURAL LIGHTING RESEARCH

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ABSTRACT

The paper discusses the technical features of the physically based computer simulation/visualization techniques for architectural lighting research. Potentials and limitations are evaluated in terms of input, algorithms, output, and analysis tools. The physically based simulation/visualization, supplemented with numeric information, is a promising tool for evaluating the luminous environment. The deficiencies are discussed to provide means of improving the usability and trustworthiness.

INTRODUCTION

Computer visualization is a powerful tool for architects, who use visualization technique as design evaluation, presentation, education, and, research tools. Visualization has always been the permanent part of the discipline, though it fluctuates in the wide range of 2D drawings to 3D modeling, rendering, animation, walk-through, and full-scale immersive/virtual environments. Most of the visualization tools are used for presentation, where the sole aim is to produce 'visually appealing' pictures. Such applications are inadequate for research and frequently misleading for design decision-making. As architectural lighting research is the subject, this paper covers only the physically based simulation/visualization.

The physically based simulation/visualization, which is supplemented with numeric information, is proposed to facilitate better understanding of light and material behavior through advanced lighting calculations. The researcher can easily alter the input data to perform qualitative and qualitative analysis of the alternative settings. On the other hand, every modeling/simulation/visualization is a simplification of phenomena. It is unavoidable to make approximations in algorithms. The matter is whether these approximations are consistent with the objectives of the research.

In an attempt to discuss the state-of-the-art computer simulation/visualization in architectural lighting research, an existing space is modeled. The simulation/visualization is done by two physically based software, Lightscape [1], and Radiance, referring to both Unix [2] and Desktop versions [3], wherever appropriate.

Lighting algorithms constitute a fundamental part in computer visualization. These algorithms are divided into three parts: light transport, light reflection, and visual display [4]. The software selection criteria are based on widespread usage and multiplicity of the lighting algorithms. Lightscape utilizes both radiosity and ray tracing algorithms. Radiosity is used to simulate the light transport and diffuse reflections while the integrated ray tracer adds specular reflections and highlights. [5]. Radiance simulates light transport and reflection using Monte Carlo backward ray tracing [6].

Fig. 1 shows the framework of the paper for physically based rendering. Technical features of the computer simulation/visualization are evaluated from lighting research point of view. The aim is to explore the potential and limitations. The deficiencies are discussed to provide means of improving the usability and trustworthiness. The discussion has 4 sections:

- Input,
- Algorithms,
- Output, and
- Analysis tools.

However, the paper is not intended for software review. IESNA Software Survey, which is prepared annually by the IESNA Computer Committee and published in LD+A Magazine, offers a detailed list of the features of currently available lighting software packages.

SIMULATION/VISUALIZATION

The setting is an elementary school classroom located in Baycity, Michigan. Classroom length, width, and height are 33, 22, and 10 feet, respectively. It receives daylight from south facing unilateral windows (24 by 2.5 feet). Daylighting is supplemented by electric lighting from ceiling mounted fluorescent fixtures. A photograph of the classroom is illustrated in Fig. 2.

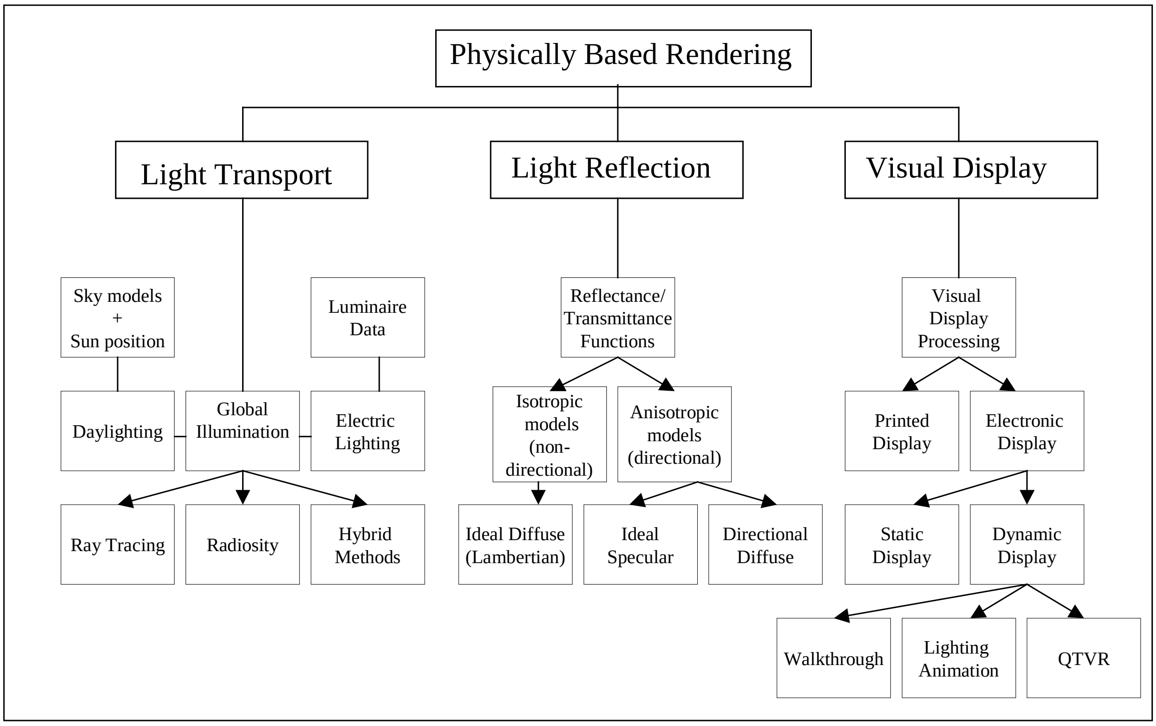


Fig. 1 The domain of physically based rendering

The study involves plausible mimicking of physical conditions, not only to simulate the appearance of the space, but also to answer various questions on:

- Illumination level on the task surface;
- Daylight variability within the course of the day and year;
- Effect of luminaire types;
- Light distribution on room surfaces and task plane;
- Luminance values of room surfaces;
- Direct and reflected glare (i.e. from blackboard, from student desks), and etc.

Fig. 2 Photograph of the classroom

INPUT

The first step of the study is the reproduction of the space as a computer-generated environment. This requires extensive information on *geometry*, *material properties*, and *photometry*. It is crucial to collect accurate data for lighting visualization and analysis. This issue has been extensively addressed by Ward and Ehrlich [7, 8]. This section discusses the means of using the collected data in the computer environment.

Creating 3D **geometry** of the scene could be handled without significant limitations, owing to the current capabilities of modeling software. Therefore, it will not be tackled here.

Physically based modeling of **material properties** is somewhat different than the physical properties of a material. Many models have been developed to describe the physical behavior of the materials in terms of color, reflectance, and transmission. Reflectance/ transmittance describes how light is reflected/ transmitted from the material. The isotropic models (non directional) define the ideal diffuse reflectance/transmittance. The anisotropic (directional) models include ideal specular and directional diffuse reflectance/transmittance. Bi-directional reflectance distribution function (BRDF) correctly predicts the diffuse, directional diffuse, and specular components of the reflected light. It is a function of the wavelength, surface roughness properties, and the incoming and outgoing directions [4]. It increases the computation time, significantly. On the other hand, the simple material models, which lessen the computation time, hamper the physical accuracy of the end result.

Modeling of material properties has impact on the quantitative and qualitative aspects of the space, like appearance, luminance values of surfaces and assessment of reflected glare. Unfortunately, the material definitions in the current software are quite controversial.

In *Lightscape*, the material properties are associated with a simple local reflectance model that supports only perfectly diffuse and ideal specular reflectivity/transparency. Lightscape does not support BRDF. It has 16 templates for predefined materials. Color is expressed as RGB [scale 0 to 1] or HVS. Texture can be applied and it alters the surface color. The physical properties have 6 parameters: transparency [0 to 1], reflectance [0 to 2], shininess [0 to 1], color blade scale [0 to 1], refractive index [1 to 2.50], and glow (cd/m^2). The user-defined materials are created through these parameters. However, only color and transparency are used during the radiosity process. Refractive index and smoothness are utilized as additional information in ray tracing [5].

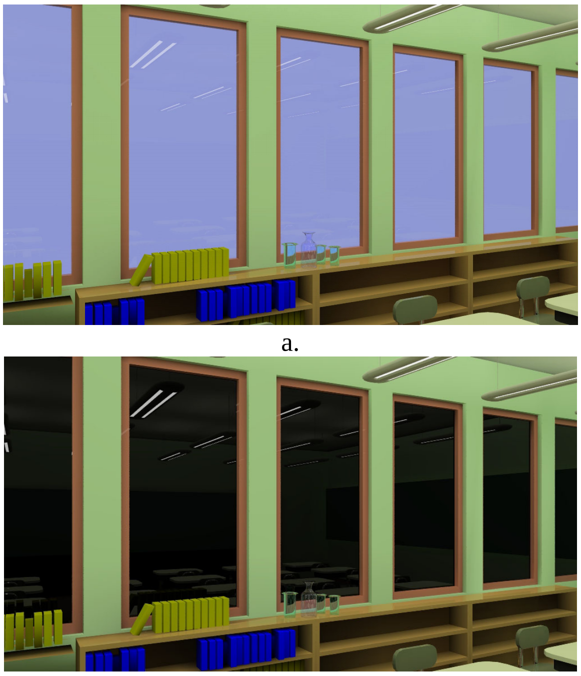
Desktop Radiance has a material library, with basic material types, i.e. plastic, metals, and transparent materials. Plastic type contains materials that have colored diffuse and uncolored specular reflections. Metal types have colored specular reflections. Both plastic and metal are defined with color (RGB), specularity and roughness. Transparent materials are defined with transmission, and transmitted specularity as well as color, specularity and roughness. Again, BRDF is not exploited and RGB values are used to calculate the hemispherical average photopic reflectance [9].

Unix Radiance has much larger material selections, with 25 material types (i.e. light, illum, plastic, metal, trans, glow, spotlight, mirror, trans, mist, interface, dielectric, anisotropic types, BRDF types) and 12 other modifier types [6].

It is clear that there is no consensus on the number and kind of the parameters that define the characteristics of a material among different software. Another problem is to express the measured quantities in terms of computer input. RGB (or VHS) is a common parameter in all software, which is used to calculate material reflectance. However RGB does not have a defined standard and its definitions vary among software. Therefore arbitrary RGB definitions result in different reflectivity. It is important to note that only Radiance has its own RGB system, which is based on CIE (International Commission on Illumination) xyY coordinates [6].

Evidently, physically based modeling of material properties is handled with many simplifications. As a result, in some instances material behavior is unacceptably erroneous. Within this framework, transparent materials deserve special attention. Different types of glass have different light admission functions, which have variety of impacts on daylighting. The current transparent material algorithms treat glass as a single layer material and there is no distinction between the inside and outside surfaces. Light transmission in glass is a dynamic phenomenon. It varies according to incidence angle of light. This unique behavior affects the indoor light levels and quality significantly. Moreover, the perception of outside view changes with the reflectance and transmittance characteristics of glass as well as the indoor and outdoor illuminance.

Fig. 3a shows close-up view of the window during daytime. Fig. 3b shows the same scene at night. As expected, it is possible to see the reflections of interior surfaces. These reflections are also present in the image, which is simulated during daytime. However in reality, reflections from glass during daytime cannot be as obvious as the nighttime, since the outside illuminance levels are overwhelmingly more than inside.


a.

b.

Fig. 3 Close-up views of the window for daytime and nighttime from Lightscape.

The discussion on glass behavior can be extended to window treatment. Windows are good examples of sources with non-constant luminance distribution. This phenomenon is critical for both quantitative and qualitative analysis. In *Lightscape*, windows are treated as diffuse light sources. A constant luminous distribution is applied, ignoring the directionality of the daylight [5]. *Radiance* offers two solutions for windows. First solution is same as Lightscape. The second approach treats the window as a transmissive material, where the glass has a non-uniform luminous intensity distribution across its surface. It takes significantly longer rendering time, but it is physically plausible [10].

The other key elements in daylight simulation are the sunlight and sky models. Direction and intensity of sunlight can be calculated based on a number of information like latitude, longitude, time, sky condition, and turbidity. Sky conditions changes unpredictably, but it is common to use CIE reference sky models for research purposes. Accurate modeling of daylight simulation enables the researcher to investigate variability through the course of the year, which is cumbersome at best, to do physically.

In *Lightscape*, the sky condition refers to the amount of the sky covered by clouds. It is possible to choose from clear, partly cloudy and cloudy skies[5]. CIE sky models are not built-in. The sky is modeled as a dome, on which the sky brightness changes depending on the position of the sun. In *Radiance*, it is possible to choose from CIE clear, Overcast, Intermediate and Uniform sky models. [9, 6]. Lightscape does not take turbidity into account while calculating the sunlight, as opposed to Radiance. The water content and turbidity of the atmosphere are major variable in sky modeling and their change alter the sky luminance distribution for a given location [11].

Photometric data of luminaires is another parameter in the simulation the luminous environment. The total luminous flux and the candlepower distribution need to be known to be able to investigate the effect of different luminaries, direct glare, and the light distribution on different surfaces and task plane.

Both software offer luminaire libraries. Real photometry of luminaire is applied through IESNA (Illuminating Engineering Society of North America) standard photometric data. It is important to realize that these photometric data contain data of a single plane. Although the total luminous flux is correct, the distribution is an average of horizontal planes [10].

ALGORITHM

Physically based light simulations contain global illumination algorithms, which describe the distribution of light in a scene. Light leaving a surface originates either by direct emission or by the reflections or transmissions within the environment. Correspondingly, light arriving a surface comes either directly from a light source or from reflections and transmissions. [12].

There are two basic algorithms for solving these complex interactions, namely **radiosity (finite element methods)** and **ray tracing**. A comprehensive survey of these algorithms is out of the scope of the paper. Some issues that are directly related to the architectural lighting research will be pointed.

Ray-tracing algorithm is view-dependent where as radiosity method is view-independent [13]. The radiosity solution allows walkthrough. In ray tracing, in order to change the view, the calculations have to be redone. Especially qualitative analysis needs information from different viewpoints, and the simulation has to be redone at each time.

The principal strength of the radiosity method is its capability of calculating the interreflections, whereas the major weakness is its restriction with Lambertian surfaces [12]. One strength of ray-tracing method is its capability of calculating specular reflections [13]. Simulation of specular reflections is important especially for qualitative analysis. Dull looking scenes with only diffuse reflections may not be adequate.

Fig. 4a shows a radiosity solution while 4b shows the same scene with radiosity and ray tracing, together. The figures reveal the difference of these algorithms at simulating glass, which has specular reflections.

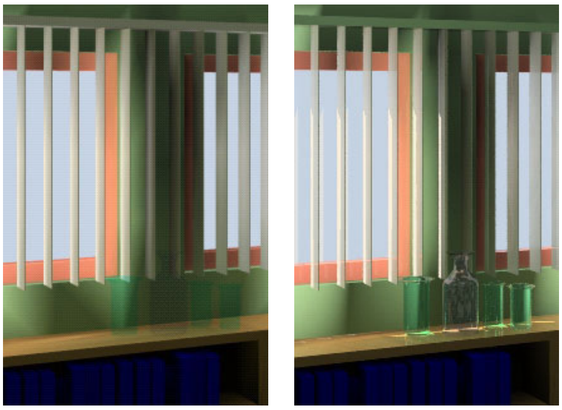

a b

Fig. 4 Close-up views of the window with a) radiosity b) radiosity and ray tracing (from Lightscape)

Fig. 5 and 6 show the Lighstcape renderings of the classroom for Dec. 21, 10:00 a.m. The former shows the radiosity solution where all the surfaces are perfectly diffuse. The latter shows the same radiosity solution with a ray tracer finish. Specular reflections and hightlights are added to the scene. Fig 7 shows the classroom with Radiance. Note that the luminaires are different in Fig. 6 and 7.

Fig. 5 Radiosity solution from Lightscape.

Fig. 6 Radiosity solution and ray tracing from Lightscape.

Fig. 7 Ray tracing from Radiance.

Algorithms delineate the quantity and quality of the results. It is wise to be skeptical about invalidated computer results. The user should also be cautious about validation studies that involve piecemeal approach where part of software is validated. In some studies, it is not clear whether the validation refers to direct light and/or inter-reflected light. It is not always clear whether the study covers all kinds of surface characteristics and geometry.

Many qualitative and quantitative validation studies have been conducted on Radiance and Lightscape [14, 15, 16, 17, 18, and 19]. These studies are valuable for a researcher. They involve comparing the software results with full-scale measurements, scale model measurements, theoretical values, and/or other lighting calculation programs. The range of the studies includes empty rooms and furnished rooms with electric lighting and daylighting. Some studies refer to direct light while others investigate reflected light as well as direct light. Some studies are confined with lambertian surfaces, whereas others explore non-lambertian surfaces and different glazing systems. The results have been evaluated in terms of image appearance, luminance and illuminance values. If accuracy is taken as the sole criterion, in all comparative studies, Radiance is found to be more accurate [17, 18, 19]. In another study, Radiance is found to be highly accurate for a range of realistic sky conditions [16].

OUTPUT

The common output is a displayed image. Lightscape outputs radiosity solution, which allows an interactive walkthrough. Radiance and the ray tracing option of Lightscape produce static images. A sequence of such images can be reproduced for walkthrough or lighting animation.

Image formats describe the means of storing the image in an electronic file. Different formats employ different compression algorithms, which have direct consequences on stored information [20]. In Lightscape, the displayed image can be saved in various formats such as bmp, tiff, SGI RGB, jpeg, gif, png, and ps. Radiance has its own image format called “pic”, which is quite different than the other common image formats. It is a map of RGB values, which contains high dynamic range [21]. It is possible to convert the “pic” format to other image formats, with the cost of information loss.

There are technical limitations that hinder the usability of a displayed image for the evaluation of lighting quality. The human visual system can process information over an enormous range of luminances, which is approximately 12 logarithmic units within a certain adaptation time. In a scene, the eye can adapt to the dynamic luminance ranges of 4 logarithmic units at once [22]. The conventional display devices cover a dynamic range of only 100:1 [23]. Regardless of source of origin, any displayed image faces this limitation. Therefore it is not possible to perceive large luminance differences, spectral characteristics or glare from a displayed image.

Nevertheless, efforts on perceptually based approaches are quite promising. There are studies that investigate the possibility of producing images that convey the appearance of the simulated scene by mapping to a set of luminances than can be produced by the display medium. The procedure is called tone mapping. Dynamic range compression modifies the luminance histogram with different techniques. Some employ linear mapping, whereas others are based on physiological and psychophysical data including adaptation levels and visual acuity [23, 24].

Desktop Radiance offers human sensitivity analysis, which is basically a variety of linear and nonlinear filters to mimic human vision [9].

ANALYSIS TOOLS

For research purposes, physically based software should provide quantitative lighting information and analysis tools besides images. Therefore, it is necessary to compute the high dynamic range of luminance and illuminance values for quantitative analysis, despite the fact that they cannot be properly displayed.

A common analysis tool is false color images (or contour lines), where a range of colors (or colored lines) between blue and red are assigned to luminance or illuminance values. Such analysis helps to visualize the luminance and illuminance distributions within a space. Tabular format of such information is beneficial for further detailed analysis.

Lightscape provides false coor images for illuminance and luminance values (Fig. 7). Numerical values on a surface can be attained in a grid format. Radiance also provides false color for illuminance and luminance values. In addition, it is also possible to perform contour plots, daylight factors, and glare analysis [25]. Fig. 8 is a luminance analysis from Radiance, where the contour plots are superimposed on the initial image. Fig. 9 is the fisheye view of the classroom with glare sources located within the scene.

FURTHER REMARKS

Evaluation of a luminous environment incorporates qualitative and quantitative analysis. Quantitative analysis deals with numerical methods. Qualitative analysis involves visual performance, visual comfort, and aesthetics, taking into account numerous factors [22]. Computer visualization of luminous environment, which is supported with numeric information, can be a powerful tool for investigating these complex relationships. The initiative is to evaluate the technical features of the physically based computer simulation/visualization techniques. The study does not involve comparative studies between the available software to point out the one that is better than the other. Rather, the discussion is carried to provide technical feedback on the capabilities and limitations of both software from researcher's point of view, which could provide guidelines to improve the usability and future implementation of physically based lighting visualization in architectural software. These points are listed as follows:

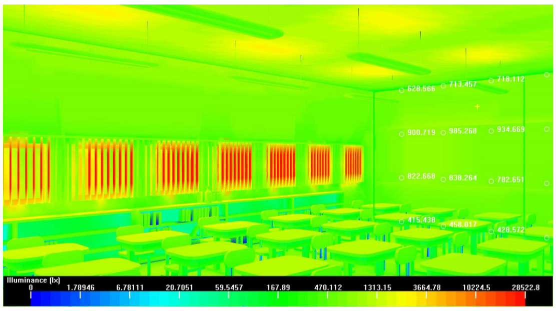


Fig. 7 Illuminance analysis with false color (Lightscape)

Fig. 8 Luminance analysis with contour lines (Radiance)

Fig. 9 Fisheye view of the classroom with glare analysis (Radiance)

- Different software have different input and output formats. The problem becomes tricky especially with material data. It is likely that the number of parameters would vary depending on the specifics of the material, but the kind of the parameters should be consistent among software.

- The computer modeling should allow the researcher to define various sky conditions besides CIE reference sky models. Likewise, the wide range of luminaire libraries is highly desirable, with the capability of creating new luminaires.

- In algorithms, simplifications are sometimes beyond physical plausibility. Therefore, it is critical to be aware of the assumptions and limitations.

- Even though the current technology is not advanced enough to display high dynamic range of luminance and color information when compared to human visual system, a proper tool for lighting research should be able to compute them. Analysis tools are positively needed for architectural lighting research.

The user friendliness of software has not been addressed deliberately. Although it is an important feature, capabilities have been given priority.

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