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Using CAD for Lighting Design

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Introduction

Part of a lighting designer's craft is imagining what a lit space will look like before it is built, but even an experienced designer can be surprised once construction gets underway. New construction materials, new techniques and experimentation lead to profitable discoveries and the occasional mistake. Design exploration is to be encouraged, as long as it does not conflict with the client's preference. Unfortunately, a client may insist on an unwise choice, resulting in confrontation and potential dissatisfaction. For these reasons and others, designers and their clients would like to preview many of these decisions before they are cast in concrete.

Computers offer the ability to predict design variables, including appearance, thereby making designer and client education more economical. By simulating the behavior of light, computers can predict luminance and illuminance levels, and make synthetic images of a space before it is built. In lighting design, common practice is to start with a target illuminance distribution, then use manufacturer's tables and simple calculations to come up with an initial lighting arrangement. For critical areas, flexibility is built into the system so that the light distribution can be tuned during installation. This approach works well in most applications, but when daylighting is a key feature, or aesthetics are stressed over illumination levels, it becomes much more difficult for the designer to be convinced, and even harder to convince the client of a quality design. Here is where a computer prediction of appearance would be invaluable.

System Requirements

In general, a computer system for the prediction of lighting should consist of a color workstation with a pointer device such as a tablet or mouse, optional input devices such as scanners or frame grabbers for obtaining material properties and textures, and optional output devices such as color printers or film recorders for recording simulation results. The platform must have enough memory and compute power to provide good interactive response time and reasonable turnaround of large batch jobs. The system should have access to large amounts of secondary storage and electronic information sources such as bulletin boards and CD-ROM catalogs to aid in the development of building descriptions.

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†Mr. Ehrlich is currently at Mack Architects, San Francisco, CA.

To maximize software connectivity and longevity, the computer should run a portable, multiuser, multitasking, networking operating system (ie. UNIX† and its derivatives from various manufacturers), and a standardized window system (such as X or NeWS) to serve as the graphics interface for interactive programs. Software running on the system should include a computer-aided drafting (CAD) program with access to expandable material, furniture and light fixture libraries, and a lighting simulation program with associated input and output translators and display drivers. The CAD program is used to create descriptions of building and room geometries which are supplemented with items from the material and fixture libraries and fed into the lighting simulation program. The lighting program then predicts the illumination levels and visual appearance of these spaces and displays its calculations on the screen or sends them to a hardcopy device.

The Radiance Synthetic Imaging System

A working prototype of the system described has been developed by the Lighting Systems Research Group at Lawrence Berkeley Laboratory (LBL), and has been in use for over three years by LBL and by the faculty, staff and students of the Architecture Department at the University of California in Berkeley (UCB). Since portable languages and operating systems permit the use of many different hardware platforms, and numerous commercial CAD systems are already available, most of this development effort has focused on the lighting simulation software, called Radiance. The Radiance system is made up of a few dozen C programs that have been compiled and run on DEC and Sun workstations, Apple Mac II's (under A/UX), a CRAY, and a number of other UNIX machines. The three main Radiance programs use ray tracing to calculate luminance and (1) display images interactively, or (2) produce picture files in batch mode, or (3) compute specific values for other purposes.

Numerous other programs provide "filtering" (translation) within and between various formats, image processing and display functions, procedural object generation, light distribution calculation, and so forth. The CAD system used most frequently to produce geometric descriptions for Radiance is GDS (Graphical Design System) from McDonnell Douglas, because it happens to be installed on the UCB architecture department machines. Although it takes little effort to write translators from other CAD formats (such as AutoDesk's DXF), limited access to these systems has curtailed LBL's translator development. Also needed are libraries of materials and fixtures, and a user friendly front end for controlling all of the programs interactively.

Lighting simulation is typically a two or three step process. The first step is describing the geometry, which is usually done within a CAD system. Note that this step is often carried out by the architect already, so it may not require much extra effort on the part of the lighting designer. The second step, if it was not included in the geometric description, is the addition of materials and fixtures from libraries and manufacturer's catalogs to complete the model for the simulation software. The third step is running the lighting simulation program and evaluating the output. As a result of this evaluation, the designer will probably return to step two, and in some cases go all the way back to step one, for another iteration. This process continues until the designer and client are satisfied that the choice and layout of the lighting system will provide the level and quality of illumination desired for the space.

†UNIX is a trademark of AT+T

In LBL's prototype system, the user must provide much of the information required by the simulation in an awkward form. A new light fixture, for example, must be entered with a text editor from the manufacturer's specification sheet, and a new wallpaper pattern must be scanned in, converted, and mapped to each surface. Simulating daylight often requires more extreme measures like running a separate program to determine the light distribution from windows and skylights. Much of this tedium could be handled by appropriate tools, but it is not within the charter of our research group to develop them. Industry cooperation and support in developing good user interfaces are essential to the success of simulation systems such as this.

Radiance Capabilities

The Radiance system uses ray tracing to simulate visible radiation in architectural spaces by following each light path backwards from its measurement point to the origin. The input to the program is the scene geometry, which describes the location and shape of every surface, and the materials, which describe how light interacts with each surface. Rays are followed from the view point into the scene, and recursively traced to other surfaces and light sources to calculate luminance. Following light paths in reverse is a much more efficient approach because only a minute percentage of the photons that are emitted enter a viewer's eyes. If light were followed from the sources, most of the calculation would be wasted on rays that were never seen. Luminance values are usually collected in a perspective map, which is a black and white image. Color images are generated by breaking the visible spectrum into three or more bands and calculating spectral interactions in parallel.

At the lowest level, the Radiance geometric model is a boundary representation with three basic surface types: polygons, spheres and cones. From these primitive shapes, compound surfaces of arbitrary complexity can be constructed. Through a process called instancing, hierarchical scenes containing millions of surfaces have been constructed. However, current CAD systems pose a practical limitation to the creation of such scenes, since they typically do not export hierarchical or procedural descriptions. There is really no reason for this restriction, except that few CAD vendors have recognized the potential of external data representations more sophisticated than polygons and polyhedra.

Basic Radiance material types include composite metal, glass, and self-luminous surfaces. Each type describes the basic interaction of light with a surface, and variable parameters determine things such as color, polish, refractive index and intensity. To these materials one can add procedural and scanned textures and patterns that add local variations to the surface orientation, color or intensity. By increasing the realism of the reflection model in this way, the viewer gets a much better feel for the lighting present in a space.

Applying Radiance to Lighting Design

Advanced simulation offers significant advantages for lighting design. Figure 1 shows a single cubicle from a partitioned office space with luminaires laid out on 8 ft centers. As is often the case, the initial lighting design did not take into consideration the spacing and location of the partitioned cubicles. Figure 1a is a Radiance calculation of the brightness distribution of one of the more poorly lit cubicles under this initial layout. The numbers superimposed on the image are the luminance values at each corresponding point in candelas per meter squared (cd/m^2). A single synthetic image represents on the order of a million luminance calculations -- far too many to digest in numeric form. The locations shown were chosen interactively by the user who ran the display program.

An improved luminaire layout accounting for the partition size and spacing resulted in values similar to those shown in Figure 1b for all the cubicles in the example office space. Placing the light fixtures more prudently thus provided better uniformity while reducing the installed power density by 43%. All of this was predicted by the Radiance lighting simulation program without having to build or measure anything.

Although luminance values may be useful to an expert lighting designer, images carry more meaning for most people. Unfortunately, the images in Figure 1 lack the detail required for casual lighting evaluation. By furnishing the cubicle with objects from a library, it is possible to get a much better idea of visibility under each lighting arrangement. Figure 2 shows the same cubicle as before, only furniture has been added to create a more realistic model of the workspace. Figure 2a shows the cubicle under the initial fixture layout, and Figure 2b shows the optimized fixture spacing. Even for the uninitiated, it is easy to get an idea of the lighting in this space from these predictions. The next question is, are we getting the right idea?

Radiance Validation

To verify its accuracy and reliability, Radiance results have been compared over the years to numerous test cases and found to be accurate within the understood limits of the calculation. However, test cases and real life are very different, so it was decided to compare a Radiance simulation to photographs and measurements of an existing space. For practical reasons of convenience and accessibility, an LBL conference room was selected as the space to be modeled on the computer. Without the benefits of a CAD system or any object or material libraries, one of the authors spent three weeks developing a computer model of the conference room from measurements, manufacturer's data and approximations.

Figure 3a is a photograph of the conference room that was modeled, and Figure 3b shows the Radiance simulation output. Small differences are noticeable in the color of objects and some reflections, but overall the two images give the same visual impression. Although efforts were made to make the computer model reasonably accurate, nothing was done that would have been difficult if the actual space were not built. This is an important point for demonstrating the viability of a prediction tool, since one would not normally have access to the space for which one is creating a model. No scanned images or patterns were used, and even colors were approximated by eye rather than measured with a colorimeter. The light distribution of the fixtures was taken from uncorrected manufacturer's data, which was probably the cause of a systematic difference in the measured and calculated illuminance values of about 30%. (Although 30% seems like a lot, this is close to the loss one would expect from lumen depreciation.)

Using Radiance for Qualitative Analysis

Because luminance corresponds so well to vision (it is this quantity that the eye actually "sees"), Radiance simulations provide enough information for a lighting designer or client to evaluate each potential solution without resorting to rules of thumb, trials or guesswork. Figure 4 shows an example where qualitative and aesthetic considerations outweigh any measurements of illumination or brightness for selecting a lighting system. Figure 4a is a simulation of an acrylic and metal sculpture illuminated at night by four globe lights located in the corners an atrium roof structure. Figure 4b shows the addition of three flood lights surrounding the base of the sculpture. The information shown in these images simply cannot be obtained from conventional lighting calculations.

Daylighting Design

Museums and galleries are places where daylight requires special attention. Appropriate lighting is needed so that visitors can enjoy the exhibit, but light can also have adverse effects on paintings and other art objects. Ultraviolet radiation, direct light and especially sunlight can cause lasting damage to many forms of artwork. Therefore, a tool that accurately predicts light levels and produces realistic images of the space in all sky and sun conditions could save not only time and money in building scale models, but ultimately the art objects themselves.

Using Radiance, one of the authors modeled the upper part of a museum that is under construction in Jerusalem, Israel. The wing under construction is lighted mostly with indirect light from skylights. The designer wanted to check the light level to insure that it would not be too low for visitors to enjoy the exhibit, or so high that it might compromise the longevity of the artwork. Figure 5 shows contour lines of equal luminance, shown in cd/m^2. The average illuminance here is about 400 lux, which is nearly eight times higher than the recommended value.

Thanks to this study, the designer discovered that the light level was generally much too high. This important issue was transmitted to the contractors who could make the necessary changes before the museum was finished.

Theater Design

The most detailed lighting design case study so far to use Radiance as a predictive tool was conducted by one of the authors who works for Mack Architects in San Francisco. In November of 1988, this firm was involved in the design of the Candlestick Point State Recreation Area Community Theater, a theater scheduled to be built by the end of 1990. The author (Charles Ehrlich), who was familiar with the GDS CAD software and Radiance, suggested that a lighting simulation be performed on the interior of the auditorium space.

The first and subsequent presentations of the simulation results over the following year revealed much more about the auditorium space that just the lighting design. Several issues of accuracy also arose when the time came to use the synthetic images to actually change the lighting design.

The most difficult concept to explain to the designers who were unfamiliar with computer simulation was that these images were not only rendered with astounding realism, but that they also were quantifiably accurate, ie. within a degree of certainty (10%) to the actual measured value of the built space. This of course assumes that the materials were assigned accurate reflectance values and that the light sources would perform according the fixture manufacturer's specifications. There were also some language difficulties relating to some of the measurement units associated with lighting design such as luminance and illuminance.

The designers determined from the first batch of images that there was a displeasing scalloped light pattern on the auditorium walls and drastically uneven patches of light on the upper edge of the balcony rail wall (Fig. 6). The seemingly obvious solution was to move the light sources closer together and closer to the walls. These decisions formed the basis of the second lighting scheme and analysis.

The above changes had a serious and unexpected side effect of causing extremely strong "hot spots" of light reflecting off of the galvanized metal catwalk edges (see Fig. 7). The contrast glare computed by Radiance at the catwalk edges was around 100. It was decided that the best solution for the harsh reflections was to lower the level of all the house lights so that their spread of light would pass mostly beneath the catwalk edges. Figure 8 shows how this decision had the effect of reducing the amount of ambient light available for illumination of the ceiling plane and proscenium arch. It was then decided that a 10% uplight version of the house light fixture would provide the extra light on the ceiling and proscenium arch viewed as desirably by the architect. The greater amount of light on the ceiling seemed to provide an uplifting feeling whereas the lower light levels on the ceiling seemed oppressive (Fig. 8). It was further deemed desirable to highlight the fact that the entire ceiling is made of compound curving scallops as prescribed by the acoustical consultants.

The most difficult task was assigning accurate colors to the surfaces that matched the samples provided by the architect. On the other hand, much benefit was gained by the exploration of the influence these different materials had in the entire ensemble of the auditorium. It was decided to paint the galvanized supports along the edges of the proscenium because they seemed to detract from the architectural sense of it being an arch.

Other costs involved in the use of Radiance included the long time required for high quality renderings with many light sources, although a new algorithm was developed to alleviate this problem. And because the construction documents were drawn with traditional ink on mylar, the computer modeling was an added expense that would have been easier to create and update if the project had been started on a CAD system.

The ultimate benefit Radiance had on the design of the auditorium is yet to be seen. As another tool at the disposal of the architect, Radiance was invaluable. The benefits were not so much in the saving of money or time, but rather in the potential aesthetic improvements. "It was like a photograph of your building before you even finish the working drawings," said Mark Mack. Few could ask for a better way to explore one's design, or sell the design for that matter.

Conclusion

We see that lighting simulation can provide valuable information not only for lighting design, but also for window selection, interior decoration, and overall architecture. This article demonstrates a lighting simulation tool that electrical system designers can use to predict both the quantity and quality of light in architectural spaces. The tool has been applied in a number of case studies and found to be realistic and accurate enough to positively influence the design process.

However, the difficulty in producing simulation models with sufficient detail is a practical limitation to computer-aided design. Conventional CAD systems are intended primarily as drawing tools and they lack certain critical features necessary for the description of a real space. For example, the room geometry is not enough to determine the appearance of a room or building; one must also know the locations and output distributions of all the light sources, the reflection and transmission characteristics of the surfaces, and the viewer's location. Until good interactive tools are developed to meet these additional data requirements, advanced simulation tools are effectively confined to the large companies and research institutions where they are created.

The technology exists to bring this type of predictive tool to the common designer, but neither government nor industry can do it alone. Software companies have produced many shining examples of good user interface design, but they generally lack the expertise to develop advanced simulation techniques. At the same time, government research institutions have produced many amazing simulation programs, but most of them take punch card style input. These two factions must act together in order to cultivate the enormous potential of the personal simulation software market.

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Editor's Note

Lawrence Berkeley Lab is making its Radiance lighting simulation software available free to anyone who wishes to develop it further. For more information, write to Greg Ward; Lawrence Berkeley Lab; 1 Cyclotron Rd., 90-3111; Berkeley, CA 94720.

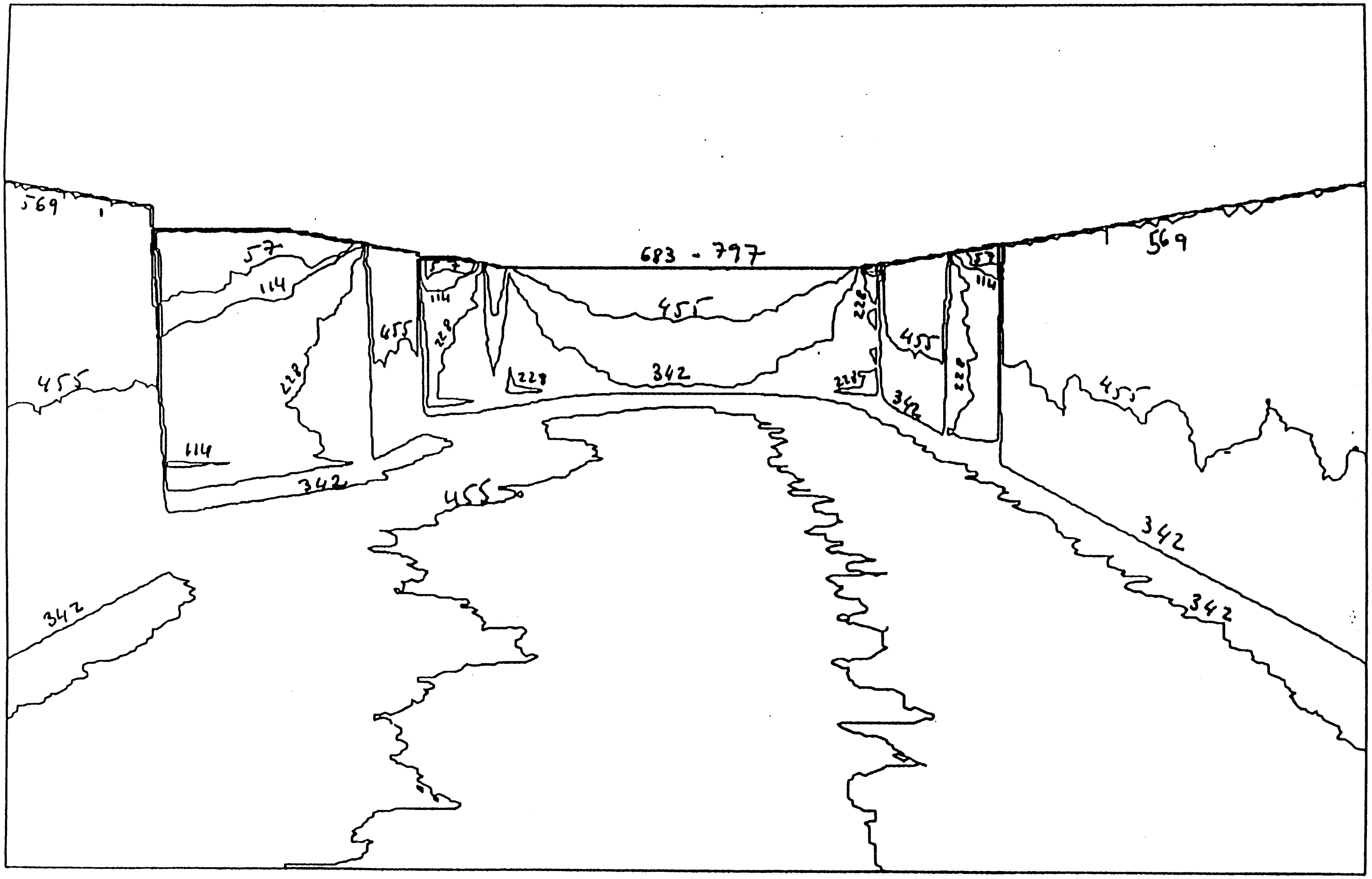
The Authors

Greg Ward is a staff scientist in the Lighting Systems Research Group at the Lawrence Berkeley Laboratory. He has a BS degree in physics from the University of California, Berkeley, and an MS degree in computer science from San Francisco State University. Mr. Ward is the originator and chief programmer of the Radiance lighting simulation system, which has been developed over the past four years.

Anat Grynberg received a BSEE degree from the University of Paris, France. She is currently a visiting researcher in the Lighting System Research Group at Lawrence Berkeley Laboratory. Ms. Grynberg's responsibilities included numerous validation studies with Radiance and contemporary lighting simulations.

Charles Ehrlich is currently employed with Mack Architects in San Francisco. He recently received a BA degree in Architecture from the University of California, Berkeley, where he first became interested in computer-aided design. Mr. Ehrlich has been one of the heaviest users of Radiance, and has offered numerous suggestions for its improvement. He also worked on the interface between the GDS drafting system and Radiance.

Francis Rubinstein received a BA degree in physics from the University of California, Berkeley. He worked at Prescolite, a major lighting fixture manufacturer, for two years where he served as a photometric test engineer and lighting designer. In 1979, he joined the Lighting Systems Research Group of the Lawrence Berkeley Laboratory as a staff scientist. Mr. Rubinstein has managed the development of several lighting analysis programs, including Radiance.



values are luminances in candela/m2