VISUALIZATION

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Two approaches to the design of lighting systems have developed over the years, embodied in the respective roles of the lighting designer and the illuminating engineer. The illuminating engineer relies on lookup tables and calculations to make lighting decisions, emphasizing the importance of light level over most other considerations. The lighting designer, in contrast, is guided by experience and aesthetic sense to illuminate environments in a way pleasing to the eye. For the illuminating engineer, the current revolution in computer technology has brought accurate illumination predictions for simple spaces, making selection more reliable and, some would argue, easier. However, the computer revolution has done little to assist the lighting designer, whose evaluation more often depends on visual qualities than on numerical quantities.

The emerging field of visualization in computer science combines calculations with computer graphics to bring another dimension of understanding to scientists, engineers, and designers. This new development holds particular promise for lighting systems design, which is both a numerical and a visual endeavor. Rather than being restricted as an engineer to a lighting decision based on a table of illuminance values, or as a designer relying only on experience, one could refer to a computer simulation that predicts quantity and displays quality.

For such a visualization tool to be valuable to the lighting designer, it must model all the complexity found in real designs, including light fixtures, surface geometries, materials, and daylight. Unfortunately, currently available lighting software is limited mostly to empty rectangular rooms with matte surfaces. The programs use flux exchange methods which rely on diffuse reflection and simple geometry to operate efficiently, and produce synthetic images that contain little more information than the illuminance tables from which they are projected. A different simulation technique, called backwards ray tracing, is suited well to computer graphics and visualization. The path of light is traced from its presumed destination to one or more sources, taking into account specular reflection, transmission, and virtually any geometry. In this way, ray tracing calculates luminance directly, which is ideal for the visualization of illuminated spaces as an image is really just a collection of luminance values. Recent advances in this technique have resulted in a complete lighting calculation that incorporates diffuse interreflection and daylight.

An efficient ray tracing package, called RADIANCE, has been developed at Lawrence Berkeley Laboratories for accurate luminance prediction, and is now ready for distribution. The program takes a scene description with light sources, sun, sky, buildings, rooms, furniture, etc. and produces spectral radiance values which can be collected in a color image. As a lighting design tool, RADIANCE represents a significant advance in the state of the art, and it is being made available to interested parties for free.

RADIANCE

RADIANCE was written initially to explore new and old techniques in lighting simulation. As a research tool, it lacks many of the user-friendly features found in commercial software packages. However, RADIANCE is more versatile than other lighting simulations and faster than other ray tracing programs, with some important capabilities not found in either. Foremost is the ability to accurately account for both diffuse and specular interreflection in complicated spaces. This is a basic requirement for the prediction of luminance in architectural applications.

RADIANCE typically operates in conjunction with a commercial CAD system, which is used to create the scene geometry. An import program takes the CAD scene description and converts it to the RADIANCE input format. Details such as surface properties are added, analysis is performed, and design modifications are made based on the result.

General

RADIANCE is currently available for minicomputers, workstations, and high-end personal computers that run the UNIX operating system. The software is divided into several components, whose relationships are shown in Figure 1. In the center are the three main programs, RTRACE, RPICT, and
RADIANCE: A software program for computing luminance and synthetic images

RVIEW, RPICT produces picture files in batch mode, and RVIEW displays scenes interactively. RTRACE calculates luminance, illuminance, and other application-specific information. The main programs are variations of the same basic ray tracer. Their input consists of scene files containing surface and material descriptions, OCTREE files produced by sorting this information (using OCONV), and auxiliary files containing information such as surface textures and candlepower distributions. Pictures produced by the programs can be displayed or sent to hardcopy devices such as film recorders and printers.

The interface to RADIANCE is command-based for maximum flexibility. Input files are created by CAD programs, text editors, and object generator programs. A mouse-based geometric editor is under development. The XFORM command permits arbitrary scaling and placement of objects in a hierarchical scene description. There is a library of useful generators to make prisms, patches, etc. and objects such as furniture and light sources are provided. The UNIX utility can be used to automate scene creation and rendering, and several other bundled programs simplify the creation of custom generators. Import programs for a few popular CAD systems will be provided.

Surfaces
At the lowest level, RADIANCE models polygons, spheres, and cones (Figure 2). From these basic boundary representations, varied and complicated shapes can be produced (Figure 3).

Continued on page 14
RADIANCE \textit{from page 5}

Scenes are composed of many objects, and these objects may in turn contain many objects. This hierarchy is constructed through a simple mechanism: command expansion. When the program comes across a command in a scene file, it executes the command and interprets the output as more scene input. In a hierarchy, the XFORM command is used to read other scene files, transforming them to new positions. These scene files may contain other XFORM commands, thus producing a tree of transformations. XFORM can also be used to create arrays of objects, such as furniture or light sources. The ability to have a command within an scene file also simplifies the use of generator programs. Rather than including the output of a program that produces a box, for example, the command itself can be included in the scene file. Changes are straightforward, and the scene description is more compact. If desired, XFORM may be used to expand all commands, creating a flat-scene description.

Although the limit to the number of surfaces in the expanded geometric model is large—around 30,000, depending on memory—it is not infinite. To permit the modeling of more complex geometries, an instance structure is introduced. If a scene contains a few objects repeated many times throughout the space, instances can share the data of those objects, requiring memory for only individual transformations (Figure 4). Using this type of hierarchical instanting, scenes with hundreds of billions of primitives can be modeled. Although rendering time does increase with the scene complexity, it is a sub-linear relationship $O(n^{1/3})$ such that an image with 1000 surfaces takes roughly twice as long as a scene with 125 surfaces, and a scene with 8000 surfaces takes four times as long.

\textbf{Materials}

Once the scene geometry has been described, the user must assign to each surface a material name, whose definition will determine how that surface interacts with light. RADIANCE provides several material types for this purpose (Figure 5). The basic type of emissive surfaces source is simply called light. Variations are provided for efficient modeling of spotlights, secondary emitters, and weak sources. Surfaces that reflect light are made of metal or plastic, and have both specular and diffuse components. Materials that transmit and refract light are also represented; glass is a common example. Within each material type, a broad range of light interactions can be simulated. For example, plastic can take on the appearance of any paint, paper, ceramic, or wood simply by varying parameters and applying optional textures and patterns.

\textbf{Textures and patterns}

Textures and patterns add important visual detail to surfaces without adding substantially to the model complexity. We define a texture as a perturbation of the surface normal, and a pattern as a perturbation of the material color. Figure 6 shows the effects of each on wood-colored plastic. A texture affects the illumination and highlights; whereas a pattern affects the reflectance.

RADIANCE provides several means for pattern specifica-
tions. A procedural pattern or texture is given as a formula that defines the pattern's value in terms of the current intersection point, ray direction, surface normal, distance, etc. The pattern in Figure 6 is related only to the three-dimensional intersection point, thus the ball appears as if it were cut out of solid wood. Patterns may also be scanned from photographs or video. Figure 7 has patterns that were digitized by a 35-mm slide scanner into picture files, then mapped onto the surfaces during rendering. The coordinate mapping for a pattern is determined by the user, and mappings from rectangular images to rectangles, cylinders, and spheres are provided. Figure 8 shows a procedural orange-peel texture and the built-in text pattern type. This illustration was inspired by an article on qualitative illumination. Textures and patterns can be combined in almost any way imaginable.

**Light sources**

Because light sources are critical to the illumination of a scene, they are given special attention by the program. In general, a light source is differentiated from other surfaces by its material type. Currently polygons, spheres, and disks may be used for local sources; area sources and odd shapes may be modeled with polygonal meshes. Distant light sources such as the sun are modeled as a special case. A non-Lambertian source distribution is modeled with a pattern whose coordinates are mapped from the output direction. A conversion from the IESNA standard format for luminaire data will be provided. If near-field photometry is available, the distribution may even be made to change over the area of the source.

**Output**

The most frequently desired output, and the type for which RADIANCE is tailored, is the color image. A color image is a two-dimensional array of radiance values rendered by projection from three-dimensions. The values are broken into spectral components, nominally red, green and blue. The renderer RPICT produces picture files in batch mode, and RVIEW calculates and displays images interactively.

Interactive image generation is an important feature of RADIANCE that permits quick error checking, view determination, and lighting evaluation. Few things are more frustrating than waiting several hours for an image, only to discover errors in the input (Figure 9). In a matter of minutes, RVIEW produces a low-resolution image clear enough to spot any
serious mistakes, and gives the user mobility to find errors
visible only from certain vantage points. One may increase
the resolution selectively, concentrating on more interesting
parts of the image. The same freedom of movement and con-
centration permits crude lighting and visibility evaluation (eg.
contrast and glare). Since a full calculation is being per-
formed at a reduced resolution, absolute accuracy is maintained.
Luminance values may be queried at any point in the scene,
with instant results. Once the scene is in order and one or
more good views have been determined, RPICF may be run
overnight to produce high resolution pictures suitable for
presentation.

The RADIANCE picture file format uses a floating point
representation for greater accuracy. Pictures may be scaled in
brightness, resized, anti-aliased, and composited digitally with
different filters provided. Drivers display the pictures on
monitors or make copies on film, video or paper. Some display
programs can superimpose numerical information on images
at selected locations for more accurate evaluation.

Figure 10 shows an atrium with luminance values cor-
responding to a few pixels in the image. The picture actually
contains a few hundred-thousand such values, more than
could possibly be displayed numerically. This combination
of quantitative and qualitative analyses is a critical aid to
design. The public domain program imagetool from the
National Center for Supercomputing Applications was used
to produce a three-dimensional plot of the picture values from
the small boxed area of Figure 8, shown in Figure 11.

Of course, images are not the only output desired from a
lighting simulation. RTTRACE provides a convenient interface
for obtaining other kinds of information from the calculation.
Individual radiance values may be computed and combined
to get luminance, contrast rendering factors, equivalent sphere
illumination, glare indices, or any other lighting metric.
Besides radiance, irradiance, intersection point, surface nor-
mal direction, and other information are available. Typically,
RTTRACE is run from a shell script or other program. For ex-
ample, the utility MAKEDIST calculates a source distribution
from a geometric specification by calling RTTRACE. This
method was used to calculate the light distribution from the
window with venetian blinds in Figure 12. By connecting cer-
tain display drivers to RTTRACE, additional information may
be computed interactively at selected image locations, such
as the illuminance on a surface or the ray propagation tree.

Validation
RADIANCE has been compared to scale model
measurements and different lighting calculation programs
in an initial validation study. Figure 13a shows calculated vs
measured values for an empty rectangular room with a single
Lambertian source. (Since SUPERLITE is primarily a day-
lighting program, the data were adapted from a skylight model
comparison.4) Figure 13b compares RADIANCE with
Lighting Technologies’ PC lighting program, LUMEN-MICRO,
for a rectangular room with four fluorescent fixtures.10 Figure
14a shows calculated and measured values for a rectangular
office with a single window under clear sky conditions.11
Figure 14b shows the same office under cloudy sky condi-

Figure 10—An atrium with direct sun. The superimposed luminance
values (in nits) sample a tiny fraction of the numerical information
contained in the picture.

Figure 11—Plot of boxed area in Figure 8. Note the lower contrast of the text
in the shadowed region.

Figure 12—Daylit office. The secondary source distribution from the
window and blinds (off left) was precalculated with MAKEDIST, which
calls RTTRACE.
These and other comparisons that have been conducted show good correlation with measured data and conventional lighting simulations. However, RADIANCE is capable of going beyond the limitations of other programs and the simple cases studied here.

The above comparisons were made with empty rooms and diffuse surfaces, exercising only a tiny subset of what RADIANCE can model. The program’s accuracy has also been verified for unempty spaces, but more work is needed in the validation of non-Lambertian surfaces. In a semi-specular model, the accurate characterization of surface reflectance properties becomes critical. Current methods require the painstaking measurement of bidirectional distribution functions using a goniophotometer. This approach is impractical given the tremendous variety of architectural materials in use, and a better method must be found for the calculation to be both valid and practical. Fortunately, there is hope of parameterizing reflectance properties and measuring their distribution functions with more conventional hardware, such as video cameras. Until this part of the validation is completed, the reflectance of semi-specular surfaces will only be approximate.

The software has been in use for the past 2 years by the Architecture Department at the University of California at Berkeley, which augments its computer modeling courses with rendering and simulation.

**Conclusion**

A new software tool for the simulation and visualization of illuminated spaces has been described. The program uses ray tracing to calculate luminance and synthetic images in complicated spaces with diffuse, specular, and transmissive surfaces. The results have compared favorably with other lighting simulations and scale model measurements in an initial
Figure 15—Shows the University of California—Berkeley architecture building, Wurster Hall, (above) and a rendering (below) constructed using McDonnell Douglas's GRAPHICAL DESIGN SYSTEM (GDS). This visualization uses RADIANCE as a back-end renderer to a commercial CAD system, yielding visual output with numerical validity. The model shown contains over 24,000 polygons and took 12 hrs to produce on a Sun 3/60.
validation study. The software is being made available at no charge in hopes that it will stimulate new research in lighting simulation and improve the quality and efficiency of lighting design.

Acknowledgements
Sincere thanks go to Francis Rubinstein for his input and support, and to the students and faculty in the Department of Architecture at UCB.

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems Energy Research and Development, Buildings Equipment Division of the US Department of Energy under Contract No. DE-AC03-76SF00098. Please write to these guys and tell them to send us some money.

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Discussion
Backward ray tracing is a viable technique for computer graphics.
1. It is incorrect for the author to say that current software can handle only simple geometry and empty rooms with little more information than an illuminance table (see Miller and Ngai, 1986 IES Conference Proceedings).
2. The technique of handling objects using XFORM is great; the calculation complexity versus number of surfaces is very good news.
3. The handling of transmissive materials is also a plus.
4. The author did not address the psychological aspects of transforming a real scene into a computer graphic image.

In 1984, Miller and Ngai considered backward ray tracing; this technique has many attractive features as stated in the paper such as handling of non-diffuse materials. There are, however, two major drawbacks:

a) Unlike flux transfer calculations, ray tracing is view-specific. Every time a new view of the scene is needed, an entirely new calculation must be done.

b) The quality of the picture depends on the number of rays traced. In order to get a good picture, a large number of calculations must be done; therefore, computational time is a problem. For example, it took 12 hrs to produce the picture in Figure 15 with a Sun 3/60. Can one use a desktop IBM PC AT, and if so, how long would it take to compute? It is fair to say, however, that as microcomputer performance improves, the time required to generate a picture will decrease.

Peter Ngai
*Peerless Lighting*

It is refreshing to see the application of a method widely used outside the lighting industry (ray tracing) to solve lighting problems. While ray tracing is used in most image synthesis software, I have never before seen an attempt to test the technique's accuracy as a predictive tool; I am glad to see it done here.

While the author is attempting to serve the lighting community by developing this program and making it available, surely he realizes that the lighting community is not a UNIX-environment running Sun computers. We are a DOS-oriented group running PCs with an occasional Macintosh (to make slides). Would the author comment on his plans to port RADIANCE to the PC-DOS environment? Also, running on a PC, what might be a typical execution time? Lastly, FORTRAN and C compilers are available for DOS to allow 80286 and 80386 processors to operate in protected, 16MB mode—in what language is RADIANCE written?

Steve Stannard
Consultant to GENLYTE

Response
The author would like to thank the discussors for their comments, which will be addressed in order.

To Mr. Ngai
The author did not mean to imply that currently all lighting software is limited to simple geometries and point calculations of illuminance. However, most commercial programs are restricted either to diffuse surfaces or regular geometries, and only recently has visualization been taken seriously in lighting simulation. Some excellent research has been done by Ngai, Miller, and others. We are hopeful that these techniques and programs will make it into general practice.

As a psychophysiological phenomenon, human vision is difficult to characterize in simple terms. A number of notable efforts have been made to determine the relationship between presentation and perception, but none have been complete-

LD + A June 1990 19
ly successful in separating the variables involved. How much of perception and evaluation depends on viewer experience, how much on visual acuity, how much on ambient environment, and so on? Until these factors are isolated, it is not really possible to compensate for variations in any one of them.

Rather than compensating for an inadequate representation of simulation results, we seek first to improve the display medium to the limits available with current technology. If it were possible to reproduce the visible wavefront at full intensity over the entire field of view, no brightness mapping would be required. The user would see and interpret things just as if the environment actually existed. As unlikely as it may seem, this ideal is perhaps not so far away. So-called virtual reality display devices are being developed for interactive computer systems, and the projected cost is comparable to current color monitors.

It is true that parts of the ray tracing calculation are viewpoint dependent. However, the parts that do not depend on view, specifically diffuse reflection, are not recalculated for every image. Just as in flux transfer, illuminance values are reused during ray tracing for many view points, and do not significantly add to the computation time after the first image. It is only because ray tracing models specular reflection, an inherently viewpoint-dependent phenomenon, that any recalculation, beyond hidden surface removal, is necessary.

Ngai is correct in his observation that the quality of an image is a function of the number of rays traced, which is directly proportional to the time required on the computer. Intuitively, there is a certain justice here. Should a better picture take more time, less time, or the same amount of time? For evaluation and debugging, turnaround time is more important than image resolution, so it is nice to be able to get output quickly at the expense of visual quality. The calculation may be just as accurate, but fewer luminance values are produced. For presentation and publication, we frequently spend as much computer time as is reasonable to get a nice looking result. On a slower machine, we would probably compromise quality for execution time.

To Mr. Stannard

The decision to develop the software in a UNIX environment was based on practicality. In the beginning, the only machines with sufficient memory and computer power were multi-user systems. By writing under the UNIX operating system, the software could be ported easily between hardware platforms, thus reducing dependence on any one machine architecture.

Although there are personal computers now with significant computing and memory resources, portability is still a problem. In the PC-DOS environment, there must be a half dozen graphics cards in common use, and many more input devices. Although the hardware of the Macintosh is somewhat stable, there are still many flavors to support and many technical volumes to read before the first menu appears.

However, the situation is not hopeless for lighting people who cannot or will not spend the additional 30 percent it takes to buy a UNIX workstation nowadays. One hope is that software standardization efforts will drag the PC-DOS community into the world of graphics windows and real operating systems. UNIX is already an option for the Mac II and some 80386 machines. Another hope is that some enterprising individual will take the C source code for RADIANCE and cram it onto an unsuspecting personal computer. Finally, there is a small weak hope that the author will acquire the funding necessary to do it himself.

There is no answer to the question of typical execution time. The interactive renderer, RVIEW, is progressive in its calculation, and is the program most frequently used by designers. The batch rendering program, RPICT, can take anywhere from a minute to several hours to compute an image, depending on the resolution requested and the scene complexity. Typically, a user will do whatever is possible in a given amount of time.

Availability

To get a copy of RADIANCE, send a 1/4-inch tape cartridge (300 ft or longer) with a prepaid return envelope to:

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