Technical Paper - Applications

DAYLIGHTING DESIGN VIA MONTE CARLO WITH A CORRESPONDING SCIENTIFIC VISUALIZATION

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ABSTRACT

A brief history of Monte Carlo methods is presented, with emphasis on uses in engineering. An overview of daylighting design is then presented, exploring both quantity and quality of light. Various strategies for achieving effectively daylit enclosures are examined, with heavy emphasis upon computation. Monte Carlo methods are the only ones which are sufficiently robust to handle specular surfaces and properties which vary with incident angle (such as for glass). A general purpose computer code, DAY3D, is developed and applied to the calculation of luminous intensities in general enclosures. Due to the requirement for huge computing resources, we perform an architectural study of photon tracing on a Cray Y/MP and a CM-2, illustrating the promise of a small CM-2 architecture for this problem. Next, we explore various strategies for visualizing both field results and the discrete Monte Carlo processes. Despite several drawbacks encountered, the information garnered by the visualizations resulted in a much greater understanding of the process, both viscerally and physically.

1. HISTORY OF MONTE CARLO

The Monte Carlo method was formalized in the 1940’s. Uses of the method have been diverse and varied since that time. However, due to computer limitations, the method has not yet fully lived up to its potential as discussed by Metropolis [Metropolis, 1985]. Indeed, this is reflected in the stages the method has undergone in the fields of engineering. In the late 1950’s and 1960’s the method was tested in a variety of engineering fields. At that time, even simple problems were compute-bound. Since that time frame, attention was focused upon much-needed convergence enhancement procedures. Many complex problems still remained intractable through the 1970’s.

With the advent of gather/scatter vector hardware and masks in massively parallel hardware, we today have a synthesized approach to vectorizing Monte Carlo problems. In his Ph.D. dissertation, Brown introduced the concept of the “event step” [Brown, 1981], enabling efficient vectorization of Monte Carlo algorithms where the particles do not interact. This approach was later successfully exploited by several investigators. Martin et al. [Martin et al., 1986] reported

1. Member, ACM, presently at University of Nevada, Reno.
speedups of a factor of five on an IBM 3090 with vector units. Nearly linear speedup was reported [Sequent Computer Systems, 1985] on a parallel architecture for photon tracing. Bobrowicz et al. [Bobrowicz et al., 1984a; Bobrowicz et al., 1984b] obtained speedups of factors from five to eight in an algorithm where particles are accumulated in queues until efficient vector lengths are obtained. Even physics algorithms such as the Los Alamos benchmark GAMTEB can be effectively vectorized [Burns et al., 1988]. Such advanced coding techniques have enabled much bigger problems to be attacked, with improved accuracy. However, there are still a host of problems which are intractable, even with an effectively vectorized algorithm. Kalos [Kalos, 1985] addresses architectural issues, including the importance of shared memory, the difficulty of load balancing, the small granularity and the high degree of logical complexity.

We now contrast transport Monte Carlo methods with the continuum approach. Transport Monte Carlo methods follow natural stochastic processes. As such, Monte Carlo methods offer the advantage of giving “fidelity to nature, to experiments, and to engineering requirements” [Kalos, 1985]. In many implementations, there is no natural time scale, to wit enough particles must be traced to achieve stationary answers, which no longer vary (at least to some small statistical tolerance) upon further increase in number of particles traced. That is, the answers must be “converged.” Maltby [Maltby, 1989] has shown for a broad class of Monte Carlo algorithms entailing Bernoulli trials, that convergence is assured. The convergence rate is proportional to the inverse square root of the number of particles traced. Thus, accuracy is assured, if the user can afford the CPU time to finish the run. This is an important distinction between Monte Carlo methods and continuum methods, which are oft subject to divergence.

However, the “inverse root N” convergence rate is slow, and many have investigated convergence enhancement algorithms. Among the most popular is splitting, where particles approaching a “target” are partitioned into multiple particles, each of which is then traced separately. This increases the number of samples which reach the target, thereby increasing statistical accuracy. This methodology is usually applied together with Russian Roulette, where particles which travel away from the “target” volume are dealt with in the converse, i.e. a random half have their characteristics doubled while the remainder are destroyed and tracing ceases for these. Heifetz [Heifetz, 1987] gives a particularly lucid explanation of these strategies. Of course, this approach is only possible where there exists a well-defined and localized target. Where accurate answers are required for entire geometries, Maltby and Burns [Maltby and Burns, 1991] have employed “inverse sampling,” where only enough particles are traced from each surface to obtain a preset level of accuracy. Thus, the emission of new particles dynamically evolves with the simulation. This method holds promise for large reductions in CPU time when tracing particles in complex geometries.

Our particular focus here is the tracing of photons in typical room geometries to provide daylighting, which displaces electrical lighting. This particular application emphasizes large-scale aspects, for which visualization is an almost essential component of debugging. To aid in our debugging process, we desire to extend the extension of “standard” visualization packages to problems of Monte Carlo type. Most if not all standard visualization packages are designed to display continuum fields. By contrast, Monte Carlo particle transport involves action at a distance. Thus, our experience was a bit like “trying to fit a square peg into a round hole.” We desired to prepare a visualization that would help to validate the model. At the same time we needed to be able to communicate the results to people both familiar and unfamiliar with the computational technique. We desired to visualize the position of the photons in the room over many event steps. In addition, we wished to color the object representing the photon according to a particular characteristic. This pro-
cess needed to be easily automated to view the positions for many event steps. Additionally, we wanted to be able to see the geometry of the room along with the objects that represented the photons. We also needed advanced rendering techniques to enhance the perception of the three-dimensional nature of the geometry and to see through some parts of the room geometry.

At the time that we started this project, there had been some preliminary work done for Monte Carlo visualization using the apE package, from the Ohio Supercomputing Center (now commercially available from Taravisual). We found that apE required a great deal of computer time and memory to render a sequence of event steps with only a few photons represented. Soon after the project started, we obtained the Advanced Visualizer from Wavefront Technologies. The Advanced Visualizer is a very general purpose animation environment. Because of its generality, we were able to adapt it to our task. Doubtless there are other software environments that could be adapted to the job (including perhaps the commercial version of apE), but the final factor was that we already had the Wavefront software in house, and it had proved to be much faster and more parsimonious of memory than apE.

Finally, as extensive CPU resources are required, we explore the suitability of traditional vector architectures and massively parallel architectures for the particular problem of interest. Large-scale problems can take many minutes, or even hours per emitting surface. Often, many design excursions are required to achieve a near optimal design. Note that we are embarking upon a design problem. In particular, we are not exploring ways to generate images, such as is typical in the field of Computer science. Rather, we are instrumenting a design tool to assist in the debugging process, and to impart physical intuition to the designer. Thus, this is an applications paper, and should be viewed in this context.

2. INTRODUCTION TO DAYLIGHTING

From time immemorial, sunlight has been used to illuminate interior spaces of shelters [Butti and Perlin, 1980; Moore, 1985]. With the advent of electric lighting, modern architecture has been freed of the constraint of placing work areas near windows. This has allowed buildings of thick cross-section to be built, providing a high ratio of internal volume to exterior surface area. Such a building geometry reduces heating and cooling loads per unit volume due to temperature differences across the building envelope and solar heat gain transmitted through the glazing.

Windows are now perceived as liabilities in conventional building design: heat is easily transferred across their relatively low thermal resistance; bothersome glare and solar gains also result. Despite these drawbacks, few commercial buildings are built without windows. Windows provide a view to the outside; promoting employee morale [Ne’eman et al., 1984; Robbins, 1986]. The color of daylight is so pleasing to the eye, that a premium is placed on light bulbs with a high Color Rendering Index, a measure of how closely the “color” of the emitted light matches the spectrum of sunlight [Kaufman and Haynes, 1981].

A physiological measure of brightness is necessary to evaluate the quantity of light necessary for sufficient illumination. Physiological brightness is a function of radiant intensity and wavelength. The photopic efficiency, plotted in Figure 1, is a measure of physiological response of the cones in the retina of the eye to the wavelength of the radiation as a fraction of its maximum sensitivity. The eye is most sensitive to light of wavelength 0.555 micrometers, thus the photopic efficiency is 1 for this wavelength. Electromagnetic radiation outside of the domain of visible light (0.38 to 0.77 micrometers) has a photopic efficiency of 0. Feynman [Feynman, 1963] presents a lucid and incisive explanation of this topic, accessible as introductory material.
The luminous intensity (flow) of light is found by integrating over wavelength the radiant power density weighted by its photopic efficiency though the visible spectrum [Thekaekara, 1974]. The photopic efficiency, plotted in Figure 1, is a measure of the physiological response of the cones of the eye with respect to wavelength. The luminous intensity [Kaufman and Haynes, 1981; Robbins, 1986] or “brightness” in lumens is given by the following

\[
\Phi_V = 683 \int_{\lambda=0.38 \mu m}^{0.77 \mu m} k_\lambda (\lambda) \Phi_R (\lambda) \, d\lambda
\]

where
\[
\begin{align*}
\Phi_V &= \text{luminous intensity (lumens)} \\
\lambda &= \text{wavelength of light (\mu m)} \\
k_\lambda (\lambda) &= \text{photopic efficiency at wavelength } \lambda \text{ (lumens/W)} \\
\Phi_R &= \text{radiant power density at wavelength } \lambda \text{ (W/\mu m)}
\end{align*}
\]

The amount of internal heat gain generated by different sources of light may be evaluated by comparing the luminous efficacy of different sources of light in the conditioned space. Luminous efficacy is the ratio of lumens in the beam (i.e., the physiological “brightness” of light), to the radiant power in the beam over a spectrum that includes visible light. In other words, luminous efficacy is the weighted average value of \( k_\lambda \) in equation (1). Since radiant power is proportional to the amount of heat generated when this beam is absorbed, a beam of high luminous efficacy will generate less heat per unit of perceived light (lumen) than a beam of low luminous efficacy.

As illustrated in Figure 2, except for buildings equipped with the latest in fluorescent light technology, the efficacy of electric lighting is approximately 2/3 that of daylight. Furthermore, if one can filter solar radiation so that only wavelengths between 0.38 and 0.77 micrometers are admitted into the conditioned space, daylight would have an efficacy of approximately 200 lumens/W, triple the efficacy of standard fluorescent lights, and more than double the efficacy of state of the art fluorescent lighting. (Note that filtering a fluorescent fixture does not increase the overall efficacy of the fixture since all of the heat still remains in the conditioned space.)

3. DAYLIGHTING DESIGN OF AN ULTRA-LOW ENERGY BUILDING

As part of the design of an ultra-low energy usage, multistory commercial office building for Colorado, we examine reducing electrical lighting loads as much as possible. To do this, we illuminate most of the interior zones of the building with daylight and provide the remainder of the lighting with photosensor controlled, dimmable, high efficiency fluorescent lighting. Since we seek to daylight a multistory building, skylights are inappropriate as the only design option; thus any design tool that we use must model inter-reflections as light from the perimeter windows bounces several times to penetrate to the rear of the room. Additionally, the skies of Colorado are extremely clear; the majority of the solar resource is direct beam radiation. As light travels from the south windows to the north side of the room via reflection, a specular reflector possesses a distinct advantage over a diffuse reflector in preserving directionality. Thus our approach requires sufficient fidelity to model specular reflectance. Similarly, transmittance of the glazing is dependant on incident angle; thus any accurate transmittance model must include a dependance upon incident angle.

To evaluate how well different geometries would perform under the above conditions, one can construct either a scale (physical) model or a mathematical model. Given identical reflective
and transmissive properties of the surfaces used in the physical model as in the proposed building, a physical model will yield a very accurate representation of daylight levels that can be expected. Problems with using a physical model are legion: (1) fabricating many geometric permutations is very labor intensive, (2) virtually no thermal data are obtained, (3) problems exist with scaling certain components (such as triple pane windows) to fit the scale model, and (4) problems also exist with simulating light intensity (particularly sky diffuse) and angles for different times of year and times of day. However, after a scoping study has been made using a mathematical model, constructing a physical model to evaluate a daylighting design is recommended. Physical modelling is perhaps the best way to obtain a qualitative evaluation of the designs that have been optimized mathematically.

Mathematical simulation is essential to provide the fidelity necessary to model specular (mirrorlike) reflections. Fortunately, a 3-D photon tracing program with the required capabilities has been developed and refined at Colorado State University. This Monte Carlo radiative exchange factor program, MONT3D, uses the efficient Maltby [Maltby and Burns, 1991] formulation to model thermal radiative transport. This program was altered to model the behavior of daylight and renamed DAY3D. To our knowledge, we are the first to employ a sophisticated Monte Carlo approach in performing daylighting design. (Recall the adage that, “if one is proficient with a hammer, then everything begins to look like the head of a nail.”)

4. THEORETICAL FORMULATION

We begin by discussing the tracing of “individual” photons. We define a single surface of the enclosure as the emitting surface, and emit photons uniformly over the area of the surface. Each is then traced from “birth” at the emission surface, to “death” on an absorbing surface, through possibly many intermediate reflections. Upon egress from a surface, the photon is traced along its trajectory to the nearest surface, whence the photon strikes, and a photon/surface interaction occurs. Using weighted probabilities that vary with incident angle for diffuse and specular reflectance and for transmittance, the disposition of the photon is determined. If reflected, its direction is changed appropriately (according to an outgoing directional distribution, either diffuse or specular - i.e. mirrorlike), and tracing continues. If absorbed, it dies, and the process is repeated for the next photon emitted. Our interest here is to count those photons passing through a fictitious work surface, located 3 feet above the floor. This work surface is used solely for tallying those photons passing downwards through it, as a measure of luminous flux, which is related to the flux of sunlight entering the enclosure (i.e. crossing the emission plane). In each wavelength band \( k \), we trace \( N^k_j \) photons from the single emitting surface, and tally the number which pass through the discretized work surfaces \( j \). This ratio is then multiplied by the incident luminous flux \( I_T^k \) to yield, in wavelength band \( k \):

\[
I_j^k = \frac{N_j^k}{N^k} I_T^k A = \frac{I_j^k}{I_T^k} A
\]

(2)

where

- \( I_j^k \) = one-way flow of light in wavelength band \( k \) from source surface to surface \( j \) (lumens)
- \( N_j^k \) = number of photons from source surface in wavelength band \( k \) passing through work surface \( j \)
- \( N^k \) = total number of photons in wavelength band \( k \) traced from source surface
- \( I_T^k \) = luminous flux in wavelength band \( k \) emanating from source surface (lumens/m²)
Due to the properties of most building materials not being readily available with respect to wavelength, we perform our simulation in a single wavelength band ($k=1$), and hereinafter drop all superscripts $k$.

If a large enough sample population is employed, the overall bulk behavior of the photons accurately represents solar radiative exchange from the environment to inside surfaces. An analytical solution to the number of photons required to achieve a given level of accuracy was formulated by Maltby [Maltby, 1990]:

$$\begin{align*}
C_j &= Z \sqrt{\frac{1 - F_j}{NF_j}} \\
\end{align*}$$

where

- $C_j$ = confidence interval (as a fraction of $F_j$) for exchange fraction to surface $j$
- $Z$ = standard random variable of the normal probability function ($Z = 1.96$ for 95% confidence)

DAY3D is designed to loop through successive emissions from the source surface until a prescribed accuracy level is attained or a maximum number of photons are emitted. The prescribed accuracy is formulated for the exchange fractions from the single source surface to a “work” surface. Note that emitting more photons improves the accuracy of all results. As rule of thumb for fairly simple geometries (around 20 surfaces), approximately 200,000 photon-bundle emissions are required to achieve answers accurate to within 2%. With mini-blinds, our simulations encompassed about 100 surfaces. For 2% accuracy, for each run, we emit 2.4 million photons, requiring about 10 minutes of CPU time on a Sun Sparc 10.

5. SOLUTION PROCEDURE

The geometry is defined by triangular or quadrilateral planes. These planes are described by the 3-D Cartesian coordinates of their vertices. Optical properties of each surface are specified versus incident angle. Both transmission and reflection are modelled with an outgoing directional dependence that may be diffuse, specular, or a convex combination of diffuse and specular. A lookup table describing the material properties is generated from the data set given. Specifically for this simulation, windows are modelled as specular transmitters and reflectors with properties varying with the incident angle, while all other surfaces are opaque and are either totally specular or totally diffuse reflectors, with properties that are constant with the incident angle. We note that there are some instances where it is necessary to account for the effects of polarization [Edwards and Tobin, 1967], but since our aspect ratio is about 3 to 1, such effects are small for our geometry.

Sunlight is modelled as radiation emitted from a plane outside the room. Direct normal (or beam) radiation is modelled as a plane wave, incident in the direction aligned with the vector from the center of the sun to the center of the earth. Diffuse radiation is modelled as isotropic, i.e. a photon has an equal probability of emission in any solid angle (weighted by projected area). Thus for each hour of the day, the program traces to all surfaces in the enclosure many photons representing incident direct beam radiation having an initial direction vector opposite to the solar azimuth and altitude. Diffuse solar radiation is modelled by one run of photons diffusely emitted weighted...
accordingly for each hour of the day to the diffuse solar intensity at that hour. Illuminance of the emission plane is calculated the same way as one would calculate the solar flux on a planar surface [Duffie and Beckman, 1991; Kreith and Kreider, 1978]. Here, we use Typical Meteorological Year (TMY) data, representing the 12 average months of the weather data collected over the past 23 years [National Climatic Center, 1981].

A completely transmitting “work” surface at a height of 3 ft. (1 meter) above the floor is subdivided into a 10 X 10 grid. The number of photons which pass through each element of the work surface are tallied. The ratio of photons which pass through the work surface to the number of photons emitted from the “environment” provides the illumination factor, $F_j$, as compared to the illumination at the emission plane. (N.b., due to multiple reflections, the sum of illumination factors for the “work” surface may, in rare instances, exceed 1.) This illumination factor is multiplied by the luminous intensity at the source plane to obtain a corresponding light level for the section of the work surface tallied. These concepts are illustrated for a south room light-shelf geometry in Figure 3. This geometry is similar to the one used in Lockheed Building 157 [Benton, 1989], but our light shelf is specular, whereas the one in Building 157 is diffuse.

Although the accuracy of MONT3D has been verified by extensive testing, the results from DAY3D have not. However, the results of DAY3D have been compared to analytical solutions for simple geometries with diffusely reflecting surfaces, as well as to actual photometric measurements from a scale model. As illustrated in Table 1, excellent agreement was obtained between the measured illuminances from the scale model collected in “real” sunlight and those simulated in DAY3D. The mean deviation (difference between measured and simulated) was less than 3% of the mean lighting level. Ergo, we regard the simulation as validated by the experimental measurements.

6. GEOMETRY

Additional detail is appropriate on the geometry of Figure 3. A lower view window 3’ in height is located 4’ above the floor. The light shelf begins 8’ above the floor and is about 2” thick (a suspended ceiling). The height above the light shelf is 3’, making the total height of the room 11’ - suitable for running ductwork in the space (11’ heights are common in commercial construction). Except for the specular light duct (top ceiling, sides and top of the light shelf), modelled as aluminized mylar with a reflectance of 0.8 [3M, 1991], all surfaces are diffuse - with a reflectance of 0.7 for the white-painted walls (including the underside of the specular light shelf) and 0.25 for the floor (brown carpet) [Gubaref et al., 1960]. Glass properties were modelled using manufacturers data for the normal transmittance [Hurd Glass, 1991] and the results of Stoke’s equations for transmittance of multiple layers of glazing (two sheets of glass and two sheets of mylar) [Duffie and Beckman, 1991; Kreith and Kreider, 1978].

In Figure 4, we provide a computer generated plot of the geometry. The view is from the top rear, outside the geometry, and shows the large emitting surface in addition to all building surfaces. This picture was constructed using the special purpose program MPLOT [Shivaswamy et al., 1992], which we have devised solely to display data associated with our Monte Carlo codes. MPLOT is capable of displaying the geometry simulated (including translations, rotations and scalings), plots of material properties, trajectories of “lost” particles, and a variety of other information useful in debugging input decks. With hundreds of surfaces, we have found it essential to access information visually. Of particular interest is locating “leaks” or “holes” in the geometry,
which result in biased answers. MPLOT runs interactively under Open Windows using the X11R5 graphical library.

7. OUTPUT QUANTITIES

7.1 Contour Plots

Contour plots of lighting levels on the work surface, located 1m (3 ft.) above the floor, are presented in Figures 5 (a) and (b) for the measured and simulated lighting levels on the work surface. In all output plots, north is up and east is to the right (i.e., the view is from above). Thus, the front of the room is down. The room is 6.1 m (20 ft.) square. The data are taken at the centroids of the 10x10 grid of the work surface, thus each grid is 0.61 m (2 ft.) square. The contour plots then cover the domain between centroids of the work surfaces. The contours are presented in units of lux (fc/m²), providing a quantitative description of light distribution but not a qualitative description of brightness or contrast.

7.2 Grey-Scale Plots

The response of the eye is very dynamic and can adjust to a fairly wide range of light levels easily. Its response is similar to the ear in that a logarithmic scale is more descriptive of the perception of relative intensities [Feynman, 1963; Kaufman and Haynes, 1981; Robbins, 1985]. We use a logarithmic grey-scale shading (using the Gouraud shading algorithm) program that qualitatively illustrates the lighting distributions. Grey-scale plots are presented in Figures 5 (c), (d) and (e). Here, we retain the same orientation as the contour plots - north is up. Each figure contains a legend, including the grey-scale intensity definitions. The scales vary for each figure, with white being the maximum, and black being the minimum.

7.3 Event-Based Videotape

Finally, we present an event-based videotape of photons as they move through the enclosure, interacting with the surfaces. A variety of views are presented, illustrating the power and flexibility of the method. In Figure 6, we present two frames from the event-based videotape. Figure 6(a) presents a view from the rear of the room, while Figure 6 (b) presents a view from the side and includes photon transport through the mini-blinds.

8. SCIENTIFIC VISUALIZATION - IMPLEMENTATION

8.1 Technology

The contour plots, although a good quantitative tool, represent old technology for visualization, and are uninteresting except as a base case with which to compare other visualization techniques. They are done “off line” on a personal computer under MS/DOS after the Monte Carlo results are obtained (i.e., post-processed). Although it is possible to implement a contouring package under X11, we have sufficient experience with contouring packages that we consider this task too daunting even to attempt.

The grey-scale plots we implemented under X11 using a Gouraud shading algorithm effected in software. Although these too are done “off line,” there is no reason we could not do them in real time as the code is executing (in fact, as these display output quantities, we could dynamically observe convergence). This technology is relatively recent, using a raster device to provide qualitative field information. Incidentally, we found a grey-scale implementation more pleasing and illustrative than a full color shading. The MPLOT program also utilizes raster tech-
nology, and has enough special-purpose requirements that we found it necessary to construct our own program. However, the implementation provides only “skeleton” views of the geometry, with no hidden line removal - this makes it appear as if the display were a stroke device.

Finally, we also generated the event-based videotape “off line.” This represents our principal contribution, and consumed most of our effort in visualization. It coincidentally produced the best results physically, as we were able to observe directly physical interactions. Additionally, it was the only we had of assessing whether the details of the code were in fact correct (it is difficult to divine through the field results whether the answers are physically realistic, but it is easy to observe whether individual physical interactions are in error). Currently, we are exploring establishing a socket between computers on the Internet to perform this in real time. We feel as if this represents state of the art technology. We now embark upon a description of production of the videotape.

8.2 Event-Based Videotape

The room geometry was translated into the appropriate object file format using a simple text editor. A faceted sphere was used to represent the photons. Only thirty-two polygons were used in the definition of the spheres to cut down on the memory requirements for the 960 photons to be traced.

The Advanced Visualizer allows a user to import the motion data as an x,y,z position. The software maintains the data in the user defined coordinate system, so the flight of the photons corresponds correctly to the room geometry. Because of the relatively small memory size of our machine, 16 MBytes, and the correspondingly large number of objects (960), only 18 frames of animation date could exist in memory at any time. To overcome this, we divided the output from the Monte Carlo simulation into files of 10 frames each. The same program that reformatted the Monte Carlo data also output a Wavefront script file that automatically cycles through the sets of frames and objects that were in memory, and read in the data set of the corresponding motion.

Included with the x,y,z position was a fourth parameter that is used to color the photons. The photons change color as they move through the geometry. Initially, all the photons are colored yellow. Photons that enter the light shelf turn pink. Photons that traverse the mini-blinds turn green. All photons turn red the instant before being absorbed.

The Advanced Visualizer does not have a facility for directly animating the color of an object. This forced us to maintain a separate object file for each of our 960 photon objects. We included special command sequences in each of these files to allow the value for the color to be substituted as the object file was read in for rendering. This procedure also required a material file with a material entry for each photon object. Each of the separate object files and the material file was created via custom Unix shell scripts. We understand that future versions of the software will allow direct animation of the material properties of an object. This will allow us to maintain only one sphere object file to be used in all 960 positions.

We choose several camera positions and rendered the file images. Each sequence (with the exception of the close-up) has 90 frames. The rendering was done without shadows or reflections. In many cases shadows and reflections can be used to improve the viewer’s perception of the three-dimensional nature of the picture. In our case, due to the fact that the light shelf is a highly specular surface and the large number of photon objects, we found reflections and shadows to be distracting to the viewer. Since shadows and reflections were turned off, each frame only required about 15 minutes of rendering time.

Naturally, we made compromises about several aspects of the visualization. In addition to the coarseness of the photon objects to save memory, we compromised on the photon’s interaction
with the walls. Surfaces in the Monte Carlo simulations are modeled as planes, and the positions of the photons are calculated for objects of zero radius. In order to see the photon during the visualization, they were given a small positive radius. Therefore when the photons interact with a surface, the photon sinks halfway into the surface before the interaction takes place.

9. RESULTS AND DISCUSSION

9.1 Contour Plots

In Figure 5(a), we show a contour plot of physical measurements taken in a scale model of the geometry. The data are presented in units of lux (lumens/m²) - the flux of light. These measurements were taken in natural sunlight which is subject to some variability. We present a corresponding contour plot deriving from the Monte Carlo simulation in Figure 5(b). The measurements consist of data taken at the centroids of each of the work surfaces, yielding 100 data points. The simulated data are the tallies of the photons numbers which pass through the 10x10 subdivisions of the work surface.

9.2 Grey-Scale Plots

The presentations in Figures 5(a) and 5(b) are useful in quantitatively assessing the data. However, it is difficult to obtain a qualitative feel for the data from contour plots. This is extremely important in determining occupant comfort - i.e. will the proposed daylighting scheme produce a pleasing effect? To illustrate these aspects, we construct grey-scale plots in 256 shades of lighting intensity. Glare has been observed to exist beyond a contrast of a factor of 30 [Robbins, 1985]. Therefore, we adopt a graduating scheme which recognizes these physiological aspects. We take as the upper limit the maximum intensity, coloring these values white. We then establish the lower limit in black as the maximum intensity divided by 30, and use linear weighting in between to obtain graduated grey scale intensities (0 is black). Viz.,

\[ \text{GrayScaleIntensity}_{\text{LINEAR}} = \text{Integer} \left( 255 \times \frac{(I - I_{\text{MIN}})}{(I_{\text{MAX}} - I_{\text{MIN}})} \right) \] (4)

But, since the eye responds logarithmically to the intensity of light. Therefore, we devise another competing graduating scheme which recognizes these physiological aspects. Here, we employ logarithmic weighting in between. Viz.,

\[ \text{GrayScaleIntensity}_{\text{LOG}} = \text{Integer} \left( 255 \times \frac{\log (I - I_{\text{MIN}})}{\log (I_{\text{MAX}} - I_{\text{MIN}})} \right) \] (5)

In Figure 5(c), we color the plot with graduated grey scale intensities varying linearly, while in Figure 5(d), we color the plot using logarithmic weighting. Figure 5(d) appears much as it would were one to enter a sunspace subject to direct beam sunlight. These plots present the measured data, as in the contour plot of Figure 5(a). Finally, in Figure 5(e), we present a logarithmic grey-scale plot of the simulated data. Note the excellent qualitative agreement between Figures 5(d) and 5(e).

9.3 Event-Based Videotape

Here, we describe the sequence of “shots” we shall show via videotape at the conference. First, we show a perspective view from the outside the upper rear of the geometry. In this view and those following, we have made some surfaces transparent so that we may “see into” the geometry,
and observe the photon interactions. This first view is intended solely to establish perspective and to illustrate the geometry.

Next, we show a view from the side of the geometry. It is appropriate to now begin discussing the details of the photon trajectories and interactions. Photons (960 in number) are released from the emitting surface in a direction coincident with the incoming beam of sunlight. The ones which strike exterior building surfaces interact in accordance with their probabilities of reflectance and transmittance. In particular, some are transmitted through the two glazings, and some are reflected from the exterior of the light shelf (and then make it through the upper glazing). Note that the ones which make it through the glazings change color from yellow to green. Of those which enter the upper light shelf, 80% are reflected specularly upon each bounce until they strike the tilted diffuse white surface at the rear of the room. Of these, 70% are diffusely reflected and backscattered into the room. Of those which enter the bottom of the room, most strike the floor where 25% are reflected diffusely into the room. Of those photons which strike the diffuse, white walls, 70% are reflected and backscattered into the room. It is easy to perceive the chaotic interactions occurring in the lower portion of the room, when compared to the orderly reflections within the light shelf.

Next, we show a close-up view of photons interacting with the mini-blinds. Here, we use 42 mini-blinds to span the space behind the window. The mini-blinds are modelled with outside surface specular, and inside surface diffuse. This is typical of the higher quality products, as it is desirable to preserve directionality in the incoming daylight with a specular reflection, and the inside surface should act much like a wall. However, we model the mini-blinds as flat when, actually, they are convex to “fan out” the incoming light. The most effective strategy for the use of mini-blinds, after using them to control the amount of light entering the space, is to use them to reflect the incoming daylight onto the underside of the light shelf - a diffuse, white surface. This, then, lights the front third of the room. The light shelf is used to light the rear two-thirds of the room. An important aspect of an effective design will be the ability to maintain a uniform spatial distribution of light - i.e., will the intensity of light diminish near the middle of the room?

We observe a variety of interactions with the mini-blinds. First, a small number of photons are transmitted straight through the mini-blinds without interaction (there are small slits open to the sunlight). Next, some bounce once and enter the room (these are reflected onto the underside of the light shelf). Additionally, some bounce twice, and are reflected onto the floor. Finally, some are absorbed. It is very apparent in this view that the spheres are modelled of finite radius, and the trajectories are modelled as point motion - the photon objects sink into the surfaces before undergoing an interaction.

Next, we show a view from above, depicting the photon transport in the light shelf. Subsequent to that, we show a view from the bottom, depicting the interactions occurring in the room. In these views, the light shelf is opaque, so as to isolate the photon interactions in the light shelf and room.

Next, we show a wide-angle view from the back of the room at the height of the light shelf, but for the first time from inside the geometry. Then we show a similar view, but from lower. In these views, the photons pass through the viewing plane - first becoming circles, then disappearing, and finally reappearing if reflected to the space in front of the camera. We conclude with the first view presented, from above and outside the rear of the geometry.
10. COMPUTATIONAL ASPECTS

Although each run consumes only a fraction of an hour, many runs must be done to effect an optimal design. An optimal design here is characterized by acceptable lighting levels over the entire work surface. To achieve this, the geometry must be varied, including location and size of the light shelf, location and size of the windows, geometry of the overhang/outside reflector, etc. To achieve the “optimal” design shown in Figure 3 (not to scale) required 45 variations on the geometry, 4 parametric variations of the material properties, 28 variations in incident angle of direct normal radiation (representing one run for each window for each hour of representative half-days in the seasons of winter, summer, and spring/fall, and two single runs involving diffuse radiation - one for each window). Taken all together, this required over 5,040 total runs - requiring over 1,600 hours of CPU time on a Sun Sparc 10. It is obvious that a supercomputer would aid greatly in performing parametric design studies.

The problem exhibits parallelism at various levels. In fact, this type of problem has been referred to as “embarrassingly parallel.” As the tracing of photons is CPU intensive, and many photons must be traced to achieve acceptable accuracy, simulating large problems via Monte Carlo is a daunting process. As mapping photon tracing algorithms to supercomputing architectures entails significant effort, we restrict our efforts to a subset of the photon tracing code. That is, we have not mapped our production algorithm to a supercomputing architecture. Rather, we strip shading, reflections and grid tracing from the code, and trace photons from emission to the first surface of intersection only, where they are absorbed. Further, we trace them in a two-dimensional, prismatic Cartesian geometry, where the tracing algorithm is simpler than it is in an axisymmetric geometry. If the approach appears to “prove out,” we can then consider taking additional steps which would relax these simplifications.

We implement our reduced algorithm on a single processor of a Cray Y/MP, and on an 8,192 node (8K) Connection Machine, Model CM-2. The Cray Y/MP is a traditional vector register machine, with hardware scatter/gather. Burns and Pryor [Burns and Pryor, 1988] have discussed vectorization of photon tracing algorithms based upon the “event step” of Brown [Brown, 1981]. In such an approach, photons in the form of vectors are passed through logical “sieves” which are formulated to filter out those photons which do not pass the requisite tests. At each stage in the multilevel sieve, a hardware gather of indices is generated using the Cray SCILIB routines WHENFLT, etc. [Cray, 19xx]. These operations are purely overhead, as no useful work results from the generation of indices, and the ensuing gathers/scatters. However, subsequent vector operations are performed on reduced vector lengths. This offers some flexibility not generally available on massively parallel architectures, where masking must be done (thus, there is no savings effected). Generally, speedup factors of around ten can be achieved from vectorization of photon tracing on Cray architectures.

An alternative architecture is the CM-2, a massively parallel architecture. The CM-2 is a data parallel architecture, where the same identical operation is performed on all of the 8K processors. On a CM-2, data are passed to and from the processors by a front end scalar machine (here, a Sun 4). On the CM-2, FORTRAN 90 is used as the language to effect parallelism via array operations. Each processor performs the same operation on its element of the array. Where logical operations are to be performed, a masking array is created (either explicitly or implicitly). Then, all processors process the data; however, on processors where the masking array is FALSE, the data for that processor are not stored. Thus, where the truth density decreases, inefficiency results. For
problems of this type, FORTRAN 90 is an extremely convenient language, due to its ability to perform array operations without do loops - each data element is mapped to an individual processor.

Normally, over 90% of the CPU time is consumed in tracing photons. As the problem is scaled up in numbers of surfaces, the photon tracing time grows as the cube of the number of surfaces, while all other times (emission, surface interaction) grow only as the square of the number of surfaces. Therefore, it is critically important to effect maximum performance on the photon tracing. The present “stripped down” algorithm is representative of emission, tracing, and absorption. During tracing, the surfaces are handled sequentially, and the photons are handled in parallel. Viz., attention is focused upon an individual emitting surface, where photons are emitted (“birth”) in parallel. Then, all photons are traced to all surfaces in the enclosure, where they are absorbed (“death”). The surfaces are handled sequentially, and the photons are again handled in parallel.

On the Cray, the surface loop is the outer, non-vector loop. The inner loops are vectorized, over photons. It is important that vector lengths be kept long, to amortize the overheads of: (1) vector start-up, (2) generation of indices, and (3) data motion. On a Cray architecture, due to the fact that the generation of indices must be done in a subroutine, this exacerbates the overhead. Tests indicate that vector lengths must be greater than about 1,000 to achieve near asymptotic speedup. Thus, for these types of problems, the Cray begins to look like a long vector machine (shades of the Cyber 205!). Further, there are some efficiencies to be gained on a Cray by compressing the photons which pass the succession of tests for intersections with surfaces into new, smaller vectors. Viz., one can eliminate up to 1/2 of the photons with simple conditionals based on the direction of flight (dot products between photon direction and surface normal direction). It is essential that the smallest vector lengths be long (i.e., for the last filter in the sieve). We began with vector lengths of 16,384 to ensure this for our problem.

On a CM-2, only the surface arrays are front-end arrays, with all photon arrays spread out over the CM-2 processors. Thus, all surface quantities are broadcast from the front end to the CM-2. Furthermore, since there are no efficiencies to be gained from eliminating only a portion of the photons from the computation (in this initial algorithm, we have not explored seeding inactive processors), we eliminate the dot product test. The algorithm was indeed much easier to map to the CM-2 due to the array structure of FORTRAN 90. There is a one to one correspondence to photon arrays and FORTRAN 90 arrays, lending itself to a direct, intuitive implementation.

CPU timings are shown in Figure 7 for both the Cray Y/MP and the CM-2. After considerable tuning, we are confident that the timings are nearly optimal for this problem on both architectures. The 8K CM-2 performs the problem in about 1/2 the time of a single processor of the Cray Y/MP. However, as shown in Figure 8, to achieve this performance, we found it necessary to increase the VP Ratio to 32. This results in the tracing of 256K photons per side - about 10 times the number required to achieve acceptable accuracy in ordinary radiative transfer applications, but about 1/10 the number required to achieve acceptable in daylighting calculations. Measured speedups on the Cray Y/MP fell into the range of between a factor of 9 and a factor of 10.

11. SUMMARY AND RECOMMENDATIONS

We have visualized both continuum field results of a Monte Carlo simulation, and the discrete events of the simulation process. The contour plots nicely complement the grey-scale plots, providing both quantitative and qualitative information. The logarithmic scale implemented for the grey-scale plots is more consistent with the physiological response of the eye. The event-based videotape is very effective at both adding new insight to the physical process. In spite of the compro-
mises necessitated by the Advanced Visualizer, we have produced a visualization that accomplishes the original goals of helping to validate the model and to communicate the results to others.

Future work in this area will allow us to improve the photon wall interaction. Another technique that might be effective would be to assign a low intensity light to each position where a photon is absorbed. A large number of photons could be visualized and the final spatial distribution of points of light would illustrate the light intensity field. It would be beneficial were the developers of visualization packages to take cognizance of the special requirements imposed by a Monte Carlo particle simulation.

Finally, both the Cray Y/MP and the CM-2 are viable architectures for effective parallelization. In our reduced test problem, the CM-2 outperformed the Cray Y/MP by a factor of two. However, the specific test problem was chosen so as to offer the maximum relative advantage to the CM-2, to assess whether it is worthwhile to proceed with an in depth study, including reflections and grid tracing. Based upon these promising results, we conclude that it is worthwhile to proceed.

Acknowledgment

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Table 1: Comparison of Measured and DAY3D Illumination Levels

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<th>Outside Ambient</th>
<th>Illumination Inside Geometry</th>
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<tr>
<td></td>
<td>Total Horizontal (lux)</td>
<td>Measured (lux)</td>
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<tr>
<td>Mean (lux)</td>
<td>55,348</td>
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<td>Std. Deviation (lux)</td>
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<td>Minimum (lux)</td>
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<td>Performance on CM-2 vs. VP Ratio</td>
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Figure 1 Phototopic Efficiency

![Phototopic Efficiency Graph]

- **Wavelength, $\lambda$ (nanometers)**
- **Phototopic Efficiency**
- **Blue**
- **Red**
Figure 2 Efficacy of Various Light Sources

- Incandescent
- Compact
- Standard
- High Efficiency
- Fluorescent Bulbs
- Total
- Sunlight

Efficacy (lumens/W)
Figure 4 MPLOT Representation of the Geometry
Figure 5 Lighting Levels on the Work Surface

(a) Measured - Contour Plot
(b) Simulated - Contour Plot
(c) Measured - Linear Grey Scale
(d) Measured - Logarithmic Grey Scale
(e) Simulated - Logarithmic Grey Scale Plot
(a) View from the Rear

(b) View from the Side, Including Mini-Blinds

FIGURE 6 Photon Trajectories from the Videotape
Figure 7 Total Execution Time vs. Number of Surfaces

Figure 8 Performance on CM-2 vs. VP Ratio