Visual Simulation of Lightning

K. Todd Reed and Brian Wyvill
The University of Calgary

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Abstract

A method for rendering lightning using conventional raytracing techniques is discussed. A particle system is used to form a lightning channel, and particular attention is paid to simulating the appearance of the lightning, including the glow around the channel as well as the effect of the lightning as it strikes an object. An object struck will also appear to glow. This is achieved by using a scalar field from which both the glow and the model can be derived.

Keywords: Computer Graphics, Lightning, Raytracing, Implicit Surfaces.

1 Introduction

The synthetic reproduction of natural scenes has been a primary goal of the computer graphics community. Much attention has been given to the problem of rendering plant life, mountainous terrain, clouds, fire, etc. Surprisingly, lightning, one of nature's most spectacular phenomena, has been largely ignored. This paper presents a simple method for modeling and rendering lightning and objects that the lightning has struck, using raytracing techniques. A particle system is used to generate a collection of segments which are joined to form a lightning stroke. For some time we have been working on skeletal-implicit surface modeling techniques and have built a number of models ([Wyvill 86a]). Such models are represented as an iso-surface in a scalar field. A method is presented for using the scalar field to provide a value for the brightness of the glow around an object that has been struck.

The paper proceeds as follows: an elementary introduction to lightning is given; an attempt to simulate lightning stroke progression by the engineering community is discussed; our approach to modeling and rendering lightning is detailed; a method for making an object glow as it is struck by the lightning is presented; followed by a summary of the results, our conclusion, and some ideas for future work.
2 A Short Course on Lightning

The best understood source of lightning is cumulonimbus, ordinary thunderstorm clouds. The majority of cloud related lightning discharges are intracloud, and are not visible from earth. Visible types of discharges include cloud-to-cloud, cloud-to-air, ground-to-cloud, and cloud-to-ground\(^1\). Lightning research has focused on the familiar cloud-to-ground lightning for the practical reason of minimizing its damaging effect on our environment. This interaction with our environment is also what makes cloud-to-ground lightning so visually stimulating. Photographs of lightning strikes that encounter “ground zero” are among the best\(^2\), and provided the inspiration for rendering lightning.

A negative cloud-to-ground discharge is initiated by the preliminary breakdown, a variation in the electric field of the lower cloud region. The stepped leader, a negative stream of electrons, branches downward in discrete intervals. The potential difference between the stepped leader and the ground, in excess of 10 million volts, attracts an upward positive leader, and the attachment process forms a channel. Once a channel is formed, the visible return stroke propagates up towards the cloud. \(J\) and \(K\) processes within the cloud may initiate a dart leader and subsequent return strokes. Unlike the stepped leader, dart leaders usually do not branch and follow the main channel. Multiple return strokes account for the flickering of lightning. The entire discharged, termed a flash, lasts about 0.5 seconds.

3 Lightning Model

In [Dellera 90], Dellera and Garbagnati simulate the path of a cloud-to-ground lightning stroke by a leader progression model, which considers the downward propagation of the stepped leader. Their model is based on the charge of the clouds, the charge of the stepped leader and upward positive leader, and the electric field strength of the surrounding atmosphere, which varies over time. The aim of the model is to assist engineers design lightning resistant structures. Consequently, the model does not effectively describe the geometry of lightning – the jagged channel shape and the branching structure – and so does not provide a basis for graphically rendering lightning. Furthermore, the mathematical complexity and the numerous parameters required to describe the complete lightning environment make the model impractical for the computer artist.

The primary goal of this research is to produce visually realistic images of lightning with minimal complexity and computational cost. Hence, the technique developed in this paper does not attempt to model cloud physics, at-

\(^1\)If you happen to be a shuttle astronaut, include cloud-to-space lightning in this list of visible discharges. On April 28, 1990, a cloud-to-space discharge was recorded for the first time by a payload-bay camera aboard the space shuttle. See [Vaughan 92] for details.

\(^2\)See [Newcott 90] for an excellent collection of lightning photographs.
moospheric conditions, or the physics of lightning discharges. Photographs of lightning from [Newcott 93] and [Uman 87] provided a yardstick for measuring the accuracy of the images produced.

3.1 Particle System Model

The skeletal structure of lightning is generated by a particle system which simulates the stepped leader progression toward ground zero. Starting with a seed segment, subsequent segments are generated by randomly rotating the seed segment. Rotating children segments with respect to the seed segment guarantees the channel assumes a linear shape\(^3\). The segments are concatenated to form a complete channel. Enough segments are generated so that the main channel hits ground zero. During the leader progression, branches are recursively generated. Branches are allocated a number of segments, chosen from a uniform distribution, and grow until its segments are depleted, or ground zero is encountered.

Uman reports that the direction changes between successive channel segments are randomly distributed, independent of segment length, with a mean absolute value of about 16 degrees [Uman 87]. This is simulated by rotating non-seed segments \(+/-\alpha\) degrees with respect to the seed segment, where \(\alpha\) is chosen from a normal distribution with mean 16 degrees and variance of about 0.1\(^4\). Segment lengths are chosen from a uniform distribution; segment lengths reportedly vary from less than 1 metre to over 1 kilometre. For the purpose of rendering, small segments provide more visually realistic results.

Branching is controlled by a probability function that may depend on how far the current channel has progressed. From the main channel, branching is more frequent near the ground. In practice, the erratic behavior of the pseudorandom number generator used\(^5\) made it difficult to consistently control branching. The lightning strokes generated were very sensitive to the seed selected for the number generator. Some seeds completely eliminated branching, while others produced excessive branching. Plate 1 shows a number of lightning skeletons generated from identical parameters, except for the random number generator seed. The angle of a branch channel with respect to its parent is chosen from a uniform distribution.

4 Rendering

Although conventional raytracing techniques are used for rendering, the line-segment representation of lightning prevents us from treating lightning strokes

\(^3\)Lightning usually obeys the philosophy that the shortest path is the best path, so most channels are linear. Nonetheless, it is not difficult to find photographs showing channels of irregular shape.

\(^4\)The variance was experimentally determined.

\(^5\)The random number generator and distributions used are from GNU's libg++. 
as geometric objects. The usual shading methods employed by raytracers are inappropriate because lightning does not have a definable surface.

The proposed shading method modifies the conventional shading algorithm by adding a color contribution from the lightning. For each ray, $r$, the following shading calculation is made:

$$ I_{\text{total}} = \sum_i I_{i_\lambda} \quad I_{i_\lambda} = m_{i_\lambda} \exp \left( - \left( \frac{d_i}{w_{i_\lambda}} \right)^{n_{i_\lambda}} \right) $$

where

- $I_{i_\lambda}$ is the light contribution from segment $S_i$ for wavelength $\lambda$.
- $m_{i_\lambda} \in [0, 1]$ is the maximum value of $I_{i_\lambda}$.
- $d_i$ is the shortest distance between the ray $r$ and the segment $S_i$.
- $w_{i_\lambda} > 0$ is half the width of the lightning channel segment $S_i$. If $d > w_{i_\lambda}$, then $I_{i_\lambda}$ is essentially zero.
- $n_{i_\lambda} > 1$ controls the contrast of the lightning channel with respect to the background. Small values of $n$ create fuzzy lightning channels, and large values ($n > 8$) create sharp lightning channels.

Plate 2 (second picture) shows a lightning channel illuminated by equation 1.

Most photographs of lightning show a strong glow surrounding the main channel of the lightning stroke. Reproducing this effect is achieved by a secondary illumination function which is added to equation 1:

$$ G_{\text{total}} = \sum_i G_{i_\lambda} $$

$$ G_{i_\lambda} = g_{i_\lambda} l_i \exp \left( - \left( \frac{d_i}{W} \right)^2 \right) $$

where

- $G_{i_\lambda}$ is the glow light contribution for wavelength $\lambda$.
- $g_{i_\lambda}$ is the maximum value of $G_{i_\lambda}$.
- $l_i \in [0, 1]$ is a "life" factor that describes the brightness segment $S_i$.
- $W$ is half the width of the glow (when $l = 1$).
- $d_i$ is the shortest distance between the ray $r$ and the segment $S_i$. 

4
Plate 2 shows the effect of adding a blue and red glow to a lightning channel (third and fourth pictures respectively).

The calculation of $d_i$ [Goldman 92] for each segment $S_i$ is a computational bottleneck. Rendering a $300 \times 300$ lightning image on an SGI 4D/310 takes in excess of 2.5 hours. By generating the lightning in a plane parallel to the view plane, the rendering process can be optimized by simplifying the calculation of $d_i$. If $L$ is the plane containing the lightning stroke to render, and $p$ is the point where the ray $r$ intersects $L$, then let $d_i$ be the shortest distance between the segment $S_i$ and the point $p$. Using this technique, rendering the same $300 \times 300$ images takes less than 30 minutes. While a boon to the time conscious artist, this method has the disadvantage of requiring the plane $L$ to be oriented perpendicular to the line of sight. Since one of our goals is to animate the lightning, we require that the lightning be consistent during camera moves, so the more general approach has to be used for animation despite the time requirement.

As the particle system proceeds, appropriate values for $m$, $w$, $n$, and $l$ are assigned to each segment. Seed values for $m$, $w$, and $n$ are input parameters, and $l$ is automatically initialized to 1.

For the main channel, $w$ is fixed for all segments, thus maintaining a uniform thickness for the entire channel. To simulate the gradual narrowing of branches, $w = 0.95w_{\text{successor}}$ for branch segments. For a primary branch seed segment\textsuperscript{6}, $w = cw_{\text{parent}}$, where $c[a, b]$ is chosen from a uniform distribution, and $0 < a < b < 1$. Branches off the main channel are consistently less than half as thick as the main channel, so $b < 0.5$ is appropriate. For non-primary branch seeds, $w = w_{\text{parent}}$.

The "life" factor, $l$, which controls the glow around a segment, is modified in a similar fashion, except for all branch seeds, $l = cl_{\text{parent}}$, where $c$ is defined as above.

All segments share the same values for $m$ and $n$.

5 Making Lightning a Light Source

Employing the method described above produces realistic lightning images which provide a good background for raytracing scenes. However, if other objects surround the lightning channel, then the lightning must behave as a light source. An expensive, but adequate solution is to add a point light source to each segment. The light source for segment $S_i$ is scaled by $l_i$, so that the main channel contributes more light than the branches. When calculating the light contribution from segment $S_i$ to point $p$ on some object the light intensity is attenuated by the scalar $1/d_i^2$; this attenuation factor prevents the lightning from illuminating distant objects.

\textsuperscript{6}A branch off the main channel.
6 Lightning Strikes

The visual effects of lightning striking an object depend on a number of factors, such as the shape of the object, the material from which it is made etc. In general, the charge spreads out over the surface of the object, and a glow is observed. Since our goal is to provide a reasonable visual impression of lightning, particularly for animation, making an object glow when it is struck is sufficient for our purposes. Since we already have a skeletal implicit surfaces system, a value for the glow can be obtained directly from the field in which such models are defined.

6.1 Skeletal Implicit Surface Modeling

The train model in plate 3 was modeled using the techniques suggested in [Wyvill 88a] and [Bloomentha 90]. In our skeleton based implicit surface system, a value for any point in space can be calculated from the implicit function, thus defining a scalar field. The surface is defined as an iso-surface in the scalar field.

The basic idea is that a model can be built from a primitive skeleton by combining elements such as points, lines, polygons, circles and splines. These elements are linked hierarchically. In general, any three dimensional object can be a part of the skeleton, as long as it is possible to determine the distance from a given point in space to the object.

The skeleton is surrounded by a scalar field \( F_{\text{total}}(P) \). The intensity of the field being the highest on the skeleton, and decreasing with distance from the skeleton. The function \( F_{\text{total}}(P) \) that relates the field value (intensity) to distance from the skeleton has an impact on the shape of the surface, and more importantly, determines how separate surfaces blend together (see [Kacic-Ales 90]).

The surface is defined by the set of points in space for which the intensity of the field has some chosen constant value (or iso-value thus the name iso-surface). Fields from the individual elements of the skeleton are added to find the potential at some chosen point. (Values can be negative or positive). The value at some point in space is calculated as follows:

\[
F_{\text{total}}(P) = \sum_{i=1}^{n} c_i F_i(P) 
\]

where \( P \) is a point in space

- \( F_{\text{total}}(P) \) is the value of the field at \( P \)
- \( n \) is the number of skeletal elements
- \( c_i \) is a scalar value (used for positive or negative elements)
• $F_i$ is the blending function of the $i_{th}$ element
• $r_i$ is the distance from $P$ to the nearest point $Q_i$ on the $i_{th}$ element.

The above expression for $F_{\text{total}}(P)$ we refer to as the explicit function for $P$, with respect to the skeletal elements. The evaluation of $F_{\text{total}}(P)$ has two steps. The first step involves finding the nearest point $Q_i$ on the skeletal element to the given query point $P$ and calculating the distance between them. This procedure depends on the geometry of the skeletal element. The second step involves evaluation of the blending function. The surface is controlled by applying local or global transformations, such as scaling, translation, and rotation, to the elements of the skeleton, and by changing the blending functions.

In our system the iso-value displayed is usually chosen to be 0.5 (see [Wyvill 86b]). Values in the field $< 0.5$ are outside the surface and values $> 0.5$ are inside. The objective is to make the field between the iso-surface and the zero contour appear to glow.

### 6.2 Achieving a glow by Raytracing

The train model in plate 3 is built from a number of ellipsoids, 14 of them have a positive effect on the field and 6 reduce the value of the field, (i.e. their contribution is subtracted from the total implicit value). The nearest distance between each ray to each primitive ellipsoid is calculated. The point on the ray is shown as $P$ in figure 1. The value of $P$ corresponding to the shortest of these distances is passed to equation 4 and the implicit value, $v$, is calculated. This value is then used to obtain the brightness of the glow as follows:

$$G_\lambda = m_\lambda v'$$  \hspace{1cm} (5)

where

$$v' = \begin{cases} 
0 & \text{if } v < 0 \\
0.5 & \text{if } v > 0.5 \\
v & \text{otherwise}
\end{cases}$$  \hspace{1cm} (6)

and $m_\lambda \in [0, 1]$ are scalars controlling the intensity of independent wavelengths. If $m_\lambda = g_\lambda$ (from equation 3), then the glow around the implicit surface will coincide with the lightning channel glow.

### 6.3 The Shape of the glow

The advantage of using implicit surface models is that the glow can be calculated directly from the field as shown above. The shape of the glow (see plate 4) follows the zero contour. Values of the field greater than zero are brighter
\[ P = R_0 + (R_d \cdot (M_0 - R_0)) R_d \]
(points are taken as vectors from the world origin)

(R\(_d\) Unit Vector in the Ray Direction)

(M\(_0\) – Modeling Primitive Origin)

(R\(_o\) – Ray Origin)

Figure 1: Finding the nearest distance from a ray to an implicit surface primitive
than the background. The two images on the left show the train model. The model contains both positive and negative skeletal elements. The upper image is rendered by adding a constant brightness to the field value. The background has a brightness value proportional to the field value, areas of black correspond to the positions of the negative objects, the train itself has already been converted to polygons and appears through the partially transparent glow. The outline of the train is the 0.5 contour. The outline of the glow is the zero contour. The negative skeletal elements have been designed to modify the shape of the train, the 0.5 contour. However, their affect on the zero contour leads to some undesirable shapes to the glow. For example, the shape of the glow at the top of the chimney has a concavity due to the negative ellipsoid. A simple solution to this problem is to ignore the negative elements when rendering the glow. The only problem is that glow does not then faithfully follow the 0.5 contour of the train, (plate 4 lower left image), however for animation purposes it was considered satisfactory.

It is also possible to change the shape of the glow, by altering the blending function used in the expression for $F_{\text{total}}(P)$. For the train we use the cubic from [Wyvill 86b] see 2. The glow field can be increased by using a function that falls to zero more slowly than the blending function for the train model itself. Again the problem with this is that the zero contour would not faithfully follow the 0.5 contour of the model. We could also use any arbitrary pair of contour levels for the model and for the glow, however most of our models have been designed for the 0.5 contour.

7 Results

This section is a gallery of lightning images showcasing the results of the above methods. The clouds in plate 3 (left image) were generated by the technique described in [Gardner 85]. Black, white, and red clouds were layered to give the impression the lightning was illuminating the clouds. The train smoke in the right image of plate 3 was manufactured from implicit surface primitives and is deliberately cartoon-like. The museum scene is in fact a frame from a short animation currently under production. Plate 5 shows the effect of adding a point light source to each segment to illuminate surrounding objects. All of the images, except the museum scene in plate 3 and plate 4, were rendered with a custom built raytracer and suffer from aliasing problems at points near thin branches. The museum scene was rendered with a modified public domain raytracer (Rayshade from Princeton University) which includes super-sampling to reduce the aliasing.
Figure 2: Cubic Blending Function $F_{cub}(r) = \frac{4}{9} \frac{r^6}{R^6} + \frac{17}{9} \frac{r^4}{R^4} - \frac{22}{9} \frac{r^2}{R^2} + 1$