



Visualization of light inside leaves of *Saxifraga rhomboidea*
by Lisa Ann Brown

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Computer Science
Montana State University
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Abstract:

Scientific visualization is a technique that can be used to relate scientific data to a graphical model. Scientific data is much more understandable when it is shown in context. Computer generated models allow data to be shown in context. This technique is especially valuable for high school and middle school students.

The amount of light present inside of a leaf was measured. Fiber optic probes were inserted into three positions in the leaf. The three positions are the palisade mesophyll, spongy mesophyll, and the interface between the palisade and the spongy mesophyll. The probes measured the light present from 400 to 750 nm in wavelength. The probes were inserted at 0 degrees, 30 degrees and 150 degrees to the leaf. This measured the transmitted light, forward scattered light, and back scattered light inside of the leaf. These three components make up the light environment inside the leaf.

A computer generated leaf model was constructed. There were four layers to the leaf, the upper epidermis, the palisade mesophyll, the spongy mesophyll, and the lower epidermis. Each leaf was constructed from a basic cell that was scaled according to natural leaf parameters in *Saxifraga rhomboidea*.

A user interface was added to the program. The interface allowed the user to change the height, width, and depth of a cell layer to reflect the natural variety inside a leaf. The interface also allowed the user to select leaf height and how dense the cells were in the spongy mesophyll.

Light data was displayed for each layer as the mouse moved over that layer of the leaf model. The user could display transmitted, reflected, or back scattered light.

When the user interface, leaf model, and light data are placed together they present a pleasing visual package to help high school and middle school students understand the role of light inside a single leaf of *Saxifraga rhomboidea*.

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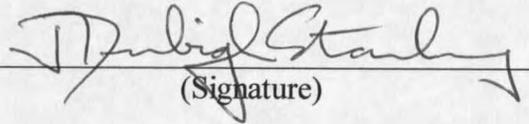
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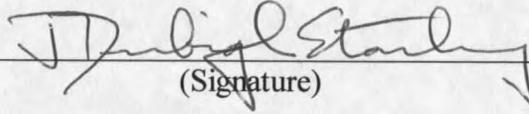
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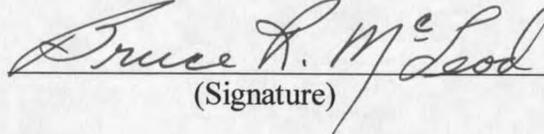
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ABSTRACT

Scientific visualization is a technique that can be used to relate scientific data to a graphical model. Scientific data is much more understandable when it is shown in context. Computer generated models allow data to be shown in context. This technique is especially valuable for high school and middle school students.

The amount of light present inside of a leaf was measured. Fiber optic probes were inserted into three positions in the leaf. The three positions are the palisade mesophyll, spongy mesophyll, and the interface between the palisade and the spongy mesophyll. The probes measured the light present from 400 to 750 nm in wavelength. The probes were inserted at 0 degrees, 30 degrees and 150 degrees to the leaf. This measured the transmitted light, forward scattered light, and back scattered light inside of the leaf. These three components make up the light environment inside the leaf.

A computer generated leaf model was constructed. There were four layers to the leaf, the upper epidermis, the palisade mesophyll, the spongy mesophyll, and the lower epidermis. Each leaf was constructed from a basic cell that was scaled according to natural leaf parameters in Saxifraga rhomboidea.

A user interface was added to the program. The interface allowed the user to change the height, width, and depth of a cell layer to reflect the natural variety inside a leaf. The interface also allowed the user to select leaf height and how dense the cells were in the spongy mesophyll.

Light data was displayed for each layer as the mouse moved over that layer of the leaf model. The user could display transmitted, reflected, or back scattered light.

When the user interface, leaf model, and light data are placed together they present a pleasing visual package to help high school and middle school students understand the role of light inside a single leaf of Saxifraga rhomboidea.

INTRODUCTION

The study of botany has always been driven by the needs of the community. When plants were used to give us food, shelter, and medicine, botanists focused on these concerns. The most useful aspect of botany at that time was the appearance of the plant. Herbariums for the collection and preservation of plant species were established in Europe in the early 1600's. Illustrators made beautiful renditions of each plant for use in further study. This was the first role of graphics in botany. Robert Hooke's invention of the microscope and publication of his book, *Micrographia*, in 1665 opened the world of microscopy to botanists. Illustrations were used to show the new world of plant anatomy. Illustrations are still used today in plant anatomy textbooks to show the internal and external anatomy of plants.

Botanists quickly embraced computers as they were introduced. Most botanists used computers for number crunching, data analysis, or mathematical models. As the power of computers and computer graphics has grown, botanists began looking at computers to illustrate scientific concepts. This is termed scientific visualization. My thesis focuses on the use of scientific visualization to show the internal light levels inside of a single leaf.

A major part of botanical scientific visualization is being able to accurately model a plant. In the late 1960's Aristid Lindenmayer inspired the current level of interest in botanical modeling. He was fascinated with the natural repetition of the placement of plant parts. Trees and plants show a natural branching structure that starts at the trunk of

the tree and repeats itself to the topmost branch. In Lindenmayer's book, *The Algorithmic Beauty of Plants*, he explores the relationship between mathematics and plant models. He proposed the first organized system of plant modeling called L-systems.

L-system is a parallel rewriting system that uses a string of symbols with associated meaning (Hammel, 1996). There is an initial string called the axiom. The right hand side of the axiom can be expanded by rewriting a right hand side symbol with another valid rule (Figure 1). The final string can be used to draw a plant. The plant from Figure 1

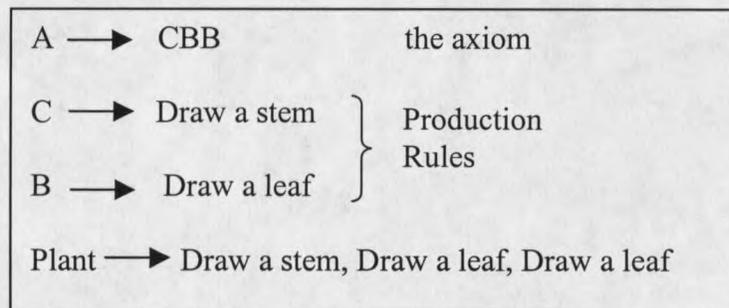


Figure 1. Example of production rules in a L-system.

would have a stem with two leaves. The most frequent way of drawing the strings is with Turtle Geometry. The string is read from left to right and the symbols are interpreted as commands to move the turtle (Prusinkiewicz, 1996). The turtle can move at any angle. The turtle also can have different line widths and colors. As the turtle moves it draws a line from its initial point to the new location. The string of symbols controls how the turtle moves. In Figure 1 the turtle would have to draw a stem, move and draw the first leaf, then move and draw the second leaf. This method of modeling looks at a plant as being a series of modules. The computer scientist can look at modules from different levels of scale. A module could be an internode and one leaf, or the module could be a

branch with 5 minor branches and 15 leaves on it. A modular system of modeling works well for branched organisms since their structure tends to be repeated. The problem with L-systems is that it is hard to control the final outcome of the plant (Power, 1999).

Modular systems led to the concept of database amplification. One of the major problems with models of complex plants or scenes is the amount of geometric data that must be stored. In order to redraw a scene, every vertex must be recorded. In database amplification, the computer scientist does not have to specify the geometry of every part of the plant. If a single stem and leaf is modeled then that same stem and leaf geometry can be reused in many ways to form a variety of plants. This reduces the amount of storage space a modeling program needs as well as reducing the amount of time needed to render a plant model (Prusinkiewicz, 1993). The concept of database amplification allowed computer scientists to generate scenes with more complex geometry. Along with database amplification, computer scientists used bounding volumes to limit the amount of a scene that must be drawn. If an orchard of trees needed to be rendered, you didn't need to render trees blocked by other trees, or trees outside of the viewing volume of the program. This also decreased rendering times in complex scenes (Marshall, 1997).

Many scientists started using models to show scientific principles. Forestry professions use visualization techniques to look at forest management problems. They use computer models that range from simple diagrams to complete and accurate virtual realities (McGaughey, 1998). A current trend in forestry management is the visualization of GIS data combined with forestry scenes. Most forestry modeling packages use the concept of modular design and database amplification discussed previously.

The use of scientific visualization is growing. More and more scientists are looking to computer graphics to show scientific principles or actions. One of the scientific principles of interest is a plant interacting with external forces. Plant growth can be altered by lack of sun or lack of water. When tree branches grow, they cannot grow where another branch exists. Roots grow around rocks rather than through them. A gardener can trim a tree to a new shape. Growth models have to incorporate external features into the graphical model. Context sensitive L-systems can adapt to the external environment and model it more accurately. In context sensitive L-systems, a production rule is only chosen if certain parameters exist. This means that even if the rule could be expanded to draw a new branch, the rule would not be expanded if there was an existing branch in that location. The string must be interpreted after each derivation step and the condition checked to see if the turtle can perform an action (Prusinkiewicz, 1994). Context sensitive L-systems are very successful in showing external influence on a model.

Other scientific events are difficult to model even with the additional power of context sensitive L-systems. Examples of these types of interactions are the movement of chemicals through the body of a plant to trigger flowering, or a plant's response to an attack by insects (Prusinkiewicz, 1994), or even the change in leaf shape as a flower bud opens (Hammel, 1992). These examples show change in a system over time. Another example of change over time is the flowering sequence of a plant. The sequence depends on external factors such as light and water but also on internal factors such as chemicals traveling through the plant to trigger bud development and opening. Animation is one way to visualize a scientific event over time. Animation can be thought of as being time

lapsed photography for computer graphics (Prusinkiewicz, 1992). Animations are based on a modified L-system. Animations do an excellent job of modeling morphogenesis in plants. Morphogenesis is the development of a plant from seed to death. Animation can capture the development of seed all the way to death of the plant. This mimics morphogenesis of that plant (Prusinkiewicz, 1996). Hammel, (1996) points out that animation may not be most suitable means of presentation for all media. When the media is print, animations do not work well since they must be shown as a series of plates. This loses the visual impact of the animation.

Even a serial selection of pictures will often show inaccuracies in the model if any are present. One of the goals of scientific visualization is to show any defects in the model that must be fixed. There are definite steps in constructing a scientific visualization. The first steps are the definition of a model and acquisition of field data. The field data must be analyzed and any parameters not measured must be estimated. The field data must then be incorporated into the model. The visualization of the model can then be constructed. Once the model is visualized it must be evaluated and the procedure started again. The goal of scientific visualization is not necessarily to produce the most accurate model possible. The accuracy is only one part of the model and does not determine the model's usefulness (Hammel, 1995). Usually, the more accurate a model is the more complex it is. This increases the time to render the model and the computer system resources needed to model it. The best model is usually considered to be the least complex model that will serve the scientific principle being demonstrated.

The purpose of my thesis is to make a model of the inside of a leaf of Saxifraga rhomboidea, which will then be used to display the internal light levels inside the leaf.

Not much research has been done on modeling the internal anatomy of a leaf (Govaerts, 1996). It has long been accepted that the internal anatomy of a leaf scatters the light inside. Some computer scientists have tried to calculate the path the light takes within the leaf (Jensen, 2001) but the changes in the internal light environment inside a leaf are difficult to model. The changes of light quality and quantity are very minute and would not be readily noticed by an observer just looking at the model. A better way to display the light inside a leaf is with a model tied to a series of graphs. The model helps the viewer understand the anatomy of the leaf and helps relate the light data in the graph to a physical construct.

This program is intended for use by High School and Middle School science students. The students should have been exposed to the internal anatomy of leaves. They should be aware that leaves have anatomical layers and that light enters the leaf. The program will allow the student observe and manipulate the variability in the anatomy of a single leaf. Students will also explore the light environment inside the leaf.

In order to achieve these goals, the model should have enough reality to the actual leaf that it can be identified but at the same time the model must not be so complex that the time to render it is too large. The leaf model should also be interactive. The user should be able to change the parameters of the leaf anatomy to reflect the natural variety found in the anatomy of a leaf. The interface of the program should be intuitive and easy to use. The light data should display clearly and quickly in response to an identification of a plant anatomy layer. This is the goal of my thesis, to create an interactive, realistic, model reflecting the internal light environment inside a leaf of S. rhomboidea.

LIGHT DATA COLLECTION

The amount of light inside a leaf can be measured very accurately. Fiber optic probes can be produced and one end inserted into a leaf to a desired depth (Vogelmann, 1984). The other end of the probe can be attached to a monochromator to measure the amount of light present of a desired wavelength at the probe tip. Light can be measured from 400 to 700 nm in wavelength. This range of wavelengths is called PAR, the photosynthetic active radiation. PAR is of interest to botanists since these are the wavelengths that play a role in plant physiology. The goal of light measurement with fiber optic probes is to analyze the amount of light available at a specific point in the leaf. The location inside the leaf is determined by the position of the fiber optic probe tip. The amount of light at the probe tip represents the amount of light available for a single chloroplast to do photosynthesis.

The light present in a leaf has four components, the wavelength, the amount of forward scatter, the amount of backscatter, and the amount of transmitted light. As light from a light source hits the upper, adaxial, surface of the leaf, the leaf absorbs about 80% of PAR while about 10% is transmitted totally through the leaf and 10% is reflected from the surface of the leaf (Monteith, 1976). The light enters the leaf through the upper epidermis. The next layer of cells, the palisade mesophyll, acts as a light pipe to pipe light down farther into the leaf (Sharkey, 1985). Light that is traveling in the leaf in a forward direction is said to be transmitted through the leaf. Light can also be scattered when it hits a boundary between an air space and cell wall. The refractive difference

between air, a refractive index of 1.0, and the cell wall, a refractive index of 1.45, causes light to scatter. Light can scatter in a forward direction or in a backward direction. There is a large amount of scattering present in the interface between the spongy mesophyll and the palisade mesophyll as well as inside the spongy mesophyll. The upper and lower epidermis also acts as a reflecting boundary. Light scattering increases the path length of photons of light and thus increases the chance that they will intercept a chlorophyll molecule and be absorbed.

Fiber optic probes can be inserted into the leaf at 0° to capture the light transmitted through the leaf. Probes must be inserted at an angle to capture the scattered component of the light. They can be inserted at 30° to capture forward scattered light and at 150° to capture back-scattered light (figure 2). When all three angles of light capture are analyzed together they represent the micro light environment inside a particular location in a leaf.

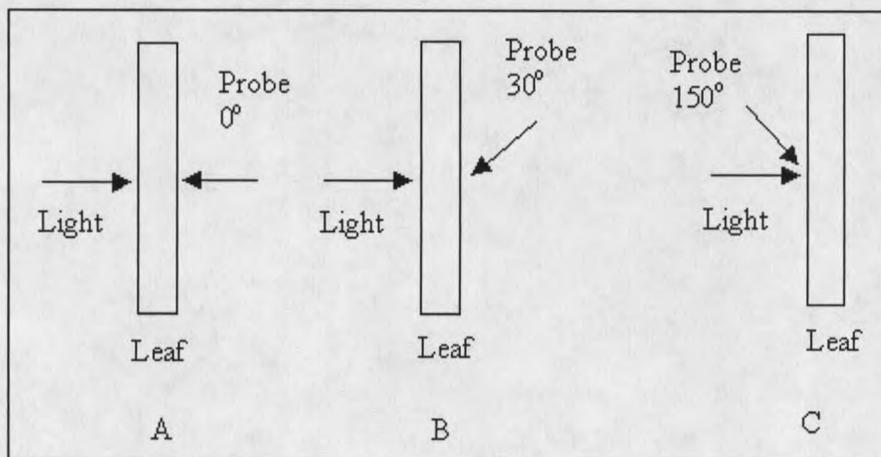


Figure 2. Direction of Fiber Optic Probe insertion into a leaf. (A) Transmitted light, (B) Forward Scattered Light, (C) Back Scattered Light.

Plant Collection

Saxifraga rhomboidea was collected in the Laramie Range and in the Snowy Mountain Range of Wyoming. S. rhomboidea is a perennial herb with a rosette of horizontal leaves at the base with a flower stalk that rises approximately 20 cm above the base. The horizontal leaves within the rosette are close to the ground. S. rhomboidea grows in sagebrush or mountain slopes early in the spring. It grows in areas that are moist, well drained and receives full sunlight. The internal anatomy of a leaf is typical for a sun leaf. Sun leaves have a well-developed palisade mesophyll and spongy mesophyll. The ratio of palisade to spongy mesophyll ranges from 1.5 to 1.3 (Evans, 1986). Sun leaves are typically thicker with a smaller leaf area than shade leaves. Plants were collected in May and transplanted into a greenhouse. Plants were brought to the lab as needed for experimentation.

Fabrication of Fiber Optic Probes

Fiber optic probes were made by cutting step index optical fiber into 61 cm lengths, removing the cladding and stretching one end into a point with a micro torch. The probe tip was then coated with platinum after which the tips were truncated with a diamond cutter. Tip diameter averaged 5 μm and acceptance angles ranged from 12° to 30° (Brown, 1994) (Figure 3).

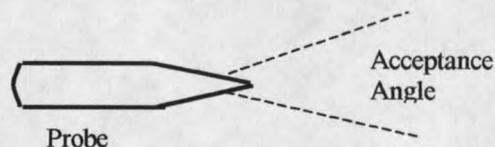


Figure 3. Fiber optic probe with tip and associated acceptance angle.

Measurement of Internal Light Microenvironment

A sun leaf from Saxifraga rhomboidea was detached from the plant. A cross section was made of the leaf and the distance from the leaf surface to the center of the palisade mesophyll, the palisade-spongy mesophyll boundary, and the center of the spongy mesophyll measured using an Olympus BH-2 microscope. The leaf was then placed in a Plexiglas leaf holder. The adaxial, upper, surface of the leaf was irradiated with collimated light at $100 \mu\text{mol m}^{-2}\text{s}^{-1}$. A fiber optic probe was mounted to a stepping motor that advanced the probe tip through the leaf to the desired location inside the leaf. Light entered the probe tip and traveled through the fiber and entered the monochromator, which was set to measure a certain wavelength of light. The probe was inserted to a position corresponding to the center of the palisade mesophyll and the amount of light measured from 400 - 750 nm. The probe was then advanced further into the leaf to a position corresponding to the spongy-palisade boundary and the light was again measured. The procedure was repeated with the probe positioned in the middle of the spongy mesophyll. Measurements were taken at a probe angle of 0° , 30° and 150° to capture transmitted, forward scattered, and back scattered light.

