## APPROVAL SHEET

**Title of Thesis:** Modeling and Rendering of Mold on Cut Wood

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Master of Science, 2005

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# ABSTRACT

**Title of Thesis:** Modeling and Rendering of Mold on Cut Wood

Aimee Joshua, Master of Science, 2005

**Thesis directed by:** Dr. Marc Olano

Often in the rendering of materials such as wood, we are satisfied with an image that is too pristine to exist in the real world. In the real world it is rare to find a piece of wood that is unblemished. Wood imperfections commonly include dirt, cracks, fungi, and mold. Of these, mold is responsible for much of the appearance we associate with weathered wood. Wood that has been cut from a tree, treated, processed, and shaped is known as cut wood. Cut wood varies in form from wood fences to wood guard posts. Cut wood that has been exposed to weather, in particular moisture and warm temperatures, is more likely to have mold form on the surface. We present a method for modeling and rendering weathered cut wood by simulating the growth and presence of mold.

We model a piece of wood as a texture map that reflects the properties of wood. A mold growth sequence is applied to the texture map to create the look of mold on wood. The technique for creating the mold growth is dependent on time and builds upon the surface of the wood model. A generalized mold growth model is implemented, reflecting the life cycle of mold over time. A subsurface scattering model is incorporated that is based on the homogeneous nature of the wood model. The mold on cut wood model is applied to two types of wood models, a plank of wood and a more complex wood object.

# Modeling and Rendering of Mold on Cut Wood

**by**
**Aimee Joshua**

**Thesis submitted to the Faculty of the Graduate School**
**of the University of Maryland in partial fulfillment**
**of the requirements for the degree of**
**Master of Science**
**2005**

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# Chapter 1

# Introduction

With the passing of time, most things, such as humans, animals, living organisms, and materials, tend to change as they age. This change occurs naturally and is affected by external factors such as the properties of the surrounding environment. In the process of graphically representing materials, it is common to not take notice of the blemishes or flaws that may exist due to time and outside factors. One of the most significant of these factors is weathering.

Weathering is the change that takes place because of the chemical and/or physical conditions of the environment. The environmental conditions of an area has an effect on the changes that these exposed materials undergo. A wood cabin, for example, will not have the same look as when it was first built because it has been outdoors for years. Over time, the cabin may begin to deteriorate because of wood-eating insects, harsh weather, and other microscopic organisms that thrive on wood.

Cut wood is one of the most familiar materials that changes appearance over time. It is commonly used in the construction of cabins, benches, and picnic tables. Of the physical assailants on wood, fungus is the most prevalent. Through the eventual emergence of fungus, cut wood takes on a weathered look that differs from its natural appearance. Stain fungi which alters the appearance of cut wood does not directly play a part in the degradation of the material. Stain fungi creates an environment which can lead to the onset of fungi that can cause decay. Mold is a type of stain fungi commonly found on cut wood. When rendering wood images, qualities such as mold should be added to create a sense of realism. Current methods of mold creation are often meant for a specific model and are not usually reproduced for a different model. The modeling and rendering of mold presented in this paper is not specific to one type of model.

In animated movies there are times when the movie will jump from present time to years into the future. It is unrealistic for a cut wood product such as a cabin to appear unchanged over this period of time. The wood would experience a number of changes including the presence of mold. A degree of mold growth would occur depending on the environment. The modeling of mold can be applied to the cabin to provide an aged look that is more realistic.

Architects and construction managers frequently make decisions in their profession in regards to materials. Depending on the environment, some materials are better than others to use in their construction. The modeling of mold on cut wood can be applied to help predict the durability and integrity of wood over time. This prediction capability can also benefit lumber yards and construction suppliers that store their wood for long periods of time.

The main contribution of this thesis is the development of a modeling and rendering scheme that allows the use of any existing wood shader as a starting point. The mold growth model accounts for each stage of the mold life cycle as well as the physical environment over a period of time.

# Chapter 2

# Related Work

## 2.1 Imperfections of Graphical Models of Wood

Often in the rendering of materials such as wood, we are satisfied with an image that is too pristine to exist in the real world. In the real world, it is rare to find objects that are unblemished. Current research in graphics has attempted to rectify this situation. Becket and Badler [1] have created an imperfection model that adds textures such as dirt, corrosion, and blemishes. This imperfection model is concerned with only a low-level of detail and uses a rule-based approach in creating and placing the blemishes. Over time even the most pristine surface can become imperfect with the appearance of dust. Based on this knowledge, Hsu and Wong [7] use the properties of a given surface, the incline of a surface and its stickiness to calculate how much dust should appear on the surface; the amount of dust will vary depending on external factors, such as wind.

The imperfections of wood on trees are captured through the use of textures. These textures typically do not show the intricate details of a tree, such as the cracks and growth marks that exist. The works of Lefebvre and Neyret [9] reflect this very shortcoming with their bark generation model. The Lefebvre and Neyret model creates cracks and fractures, using the properties of bark growth to form simulation rules. The cracks and fractures of the bark that are produced add an element of time and aging to the trees.

## 2.2 Simulation Modeling

Computer simulations of biological processes are characterized as models that are similar to that of the biological process. A common mathematical model that is used to simulate the growth and behavior of biological organisms is cellular automata. Cellular automata have four features that describe the model: geometry, states, neighbors, and rules of change. The geometry of cellular automata is the grid of cells that are being modeled. Each cell of the grid is identified by the state that is associated with the cell at a given time. A neighbor of a cell is any cell that immediately surrounds it. Criteria that define the behavior of each cell are known as the rules of change. Whenever the rules of change are applied to the geometry, a new generation of that biological organism is produced [18].

The Game of Life is the leading example of Cellular Automata. Developed by John Conway in 1970, the Game of Life explores the evolution patterns of a population given an initial state and a set of rules. The game is based on the idea that a cell exists in one of two states, live or dead. If a live cell has two or three neighbors then it continues to live. Anything less than two or more than three living neighbors will cause that live cell to change states to dead. A dead cell can become live if it is surrounded by exactly three live neighbors. Each cell is dependent on the state of its surrounding cells at any given time. As time passes, the life and death of a population is simulated [3].

The finite element method are a different type of simulation that uses models that are geometrically similar to the object or system being modeled. The geometric model is subdivided to create smaller elements or parts that can be connected to reproduce the geometric model. This division process is known as discretization. The properties of the smaller parts are combined together to determine the properties of the model as a whole. These properties can then be related to the system or object that it represents. Finite element methods have been applied to various disciplines of engineering including fluid flow. The use of finite element methods with fluid flow can be used to find the air flow over an airplane wing. Given properties of the wing, finite elements can discretize the wing to calculate the force and drag over the surface[13].

## 2.3 Weathering of Graphic Models

Time is a characteristic of models that is not normally accounted for during rendering. Over time, materials begin to change due to aging and environmental effects. We characterize this as weathering. Figure 2.1 shows the effects of weathering on a guard rail (a), a wood fence (b), and a picnic table (c) from Patapsco State Park in Baltimore, MD. These cut wood products have been outdoors for an extended period of time. Unfortunately, work

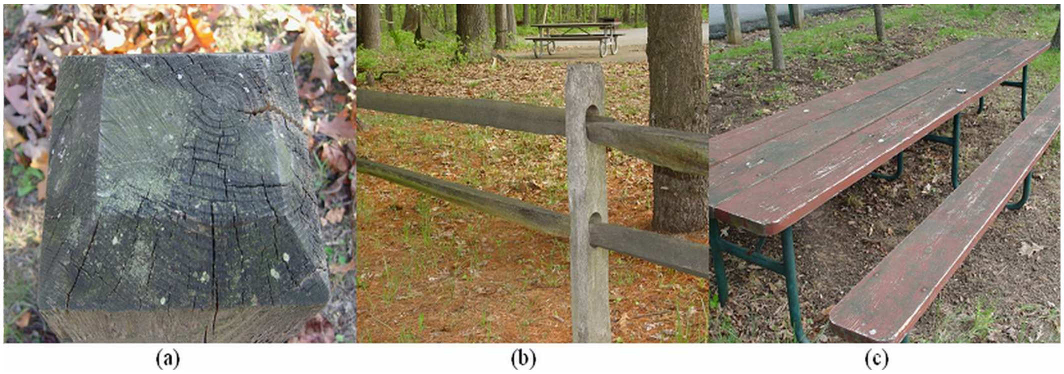



Figure 2.1: Weathering effects on wood

in the graphics literature regarding the effects of weathering on materials in the environment are sparse. Dorsey and Hanrahan began the foray into the area of realistic material rendering [5] by modeling the surface of metallic patinas. Patina is a glaze or sheen on a surface due to age and use. The patinas are represented as a series of homogeneous layers. Operators are applied to these layers to produce the desired weathering. Some of the operators implemented include erosion, coating, and polishing of the surface. For reflectance and transmission of light they use the Kubelka-Munk model. The Kubelka-Munk model calculates the diffuse colors of a surface as a result of subsurface scattering. These patinas can then be applied to more varied structures such as copper statues and domes.

Dorsey continued her research in the area of weathering with her work on weathered stone. Dorsey et al. [4] build upon the research of metallic patinas by moving from two dimensional surfaces to three-dimensional volumes. Instead of representing the stone as a series of layers, Dorsey et al. use slab data structures, which contain both surface and volume based object representations. Stone is non-homogeneous in nature and is comprised of various minerals. This presents an additional challenge to model weathering attempts. The weathering model used by Dorsey et al. simulates the flow of water and the effect weathering has on the minerals that make up the stone. These same minerals have an influence on both the appearance of the translucency and coloring of the stone surface. The results are then rendered using a Monte Carlo based ray tracer.

The subsurface scattering of light that occurs within materials that are homogeneous in nature play a part in rendering. Hanrahan and Krueger [6] present a reflectance model that is made up of the standard surface reflectance and the subsurface reflectance from back scattering through layered surfaces. It is an appropriate model to use with homogeneous layered materials. Jensen et al. [8] build upon this, providing a model that is meant for homogeneous layered material but also models subsurface transport from one point to another allowing for it to properly model translucent material. A direct implementation of this model is available in the 3Delight renderer [20].

## 2.4 Wood Processing

Trees are comprised of wood and protected by an outer layer of bark. Of the world's natural resources, wood is used often for a variety of purposes. It is used for lumber, paper, fuel, and much more. The cellular structure of wood is made up of a variety of chemical components: cellulose, lignin, hemicellulose, and extractives. Differences in the volumes of these chemicals and the cellular structure confer different qualities to the wood such as strength and density. After a tree has been harvested or cut down, it is processed. There are a number of ways to process wood, however, the most common processing method is *treatment*.

If harvested wood is left untreated, it is more susceptible to biological deterioration. The chemical composition of wood contains sugars and starches which are natural sources of food for insects, fungus, and other organisms. The presence of organisms consuming these sugars and starches can lead to wood damage. The treatment of wood does not entirely eliminate the possibility of biological deterioration, however, it does defer this type of breakdown.

The process of treating wood involves adding preservatives to the wood, which increase its ability to resist biological deterioration that can occur [10]. Cut wood which has been harvested and shaped is treated in this fashion. Next to trees, cut wood is the most common visible form that wood can take. Cut wood is also found outdoors as building material in items such as picnic tables, benches, and cabins. These types of cut wood have an increased susceptibility to fungus because the environment provides constant exposure to moisture.

## 2.5 Composition of Fungi

Fungi are categorized as a large group of plants that do not contain chlorophyll. Fungi grow from spores and have the ability to reproduce at an extremely high rate. Upon germination, spores grow hyphae which are threadlike filaments that form the body of a fungus. As hyphae continue to grow and spread, they are collectively called mycelium[14]. A visual representation of mold can be seen in Figure 2.2. There are certain basic requirements that all fungi need to sustain themselves as shown in Table 2.1 [2, 10]. Given these requirements, cut wood found outdoors is a natural habitat for fungi to sustain themselves. Fungi

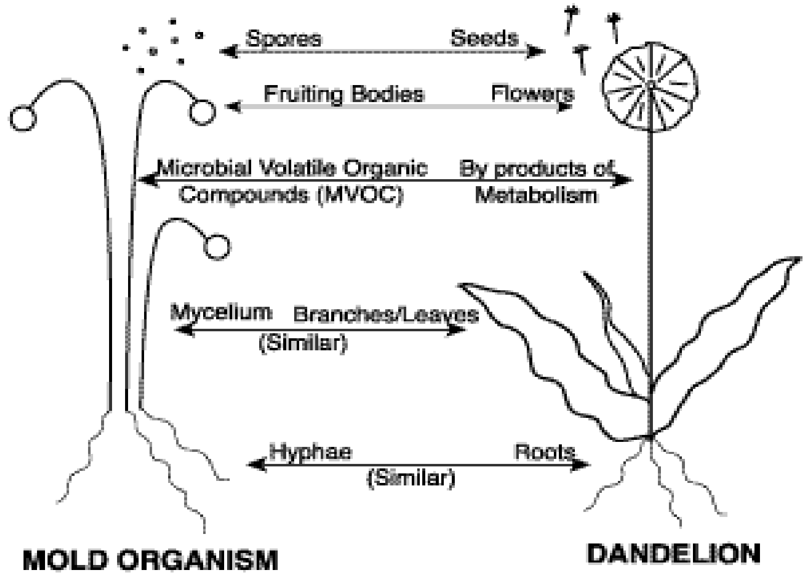



Figure 2.2: Similarities between a mold organism and a dandelion. Image courtesy of Disaster Restorations[15]

can be classified into two types, decay fungi and stain fungi. Decay fungi attack the nutrients and composition of wood resulting in the deterioration of wood. Stain fungi do not decay wood but have an effect on the appearance of wood [10]. In addition, stain fungi do not directly damage wood like decay fungi. They do, however, create an environment that is ideal for decay fungi to thrive [22].

Mold is a type of stain fungus and is more likely to be found on cut wood than a living tree. After a tree has been harvested, the ability of the wood to protect itself declines due to the removal of the bark. The bark of a tree protects the wood by denying fungi and mold access to the nutrients they need to grow. Once the wood has been cut and processed these nutrients are readily accessible [16]. Mold may not be the most damaging factor in wood decay, but its effects are significant in the longevity of cut wood.

Fungi go through three stages during their life: spore germination, mycelium growth, and sporulation. While reproduction occurs during the third phase of sporulation, fungi still undergo growth during the first two stages. As time passes and fungi grow, they also age similar to other biological organisms. For this reason, fungi experience a fourth stage in their life cycle, moribund.

Fungi grow radially over time as the hyphae spread at a constant rate. As the hyphae grow it will begin to branch. The branching has a monopodial quality where there is one central branch with offshoot branches possible [17]. The unpredictable nature of fungi make it difficult to apply a conventional growth model.

The Biohygrothermal model is a model for spore germination proposed by Sedlbauer et al. [19]. The basis of the Biohygrothermal model is that the moisture content within a spore is dependent predominantly upon the environmental relative humidity. As relative humidity increases in an environment so does the probability of fungal growth. However, this model does not provide an entirely accurate reflection of mold growth. Mold is not reliant solely upon relative humidity, but rather on a combination of all four of the requirements shown in table 2.1. Because of the complexities of the growth of mold, there is no one model that is widely accepted in this area. We use an overall generalized growth model for this reason. The generalized growth model takes into account the environment and life cycle

| Requirement | Condition |
|---|---|
| Temperature | Between $50^o$ and $90^o$ F |
| Moisture | 20% or more |
| Oxygen | Adequate |
| Food source | Cellulose, Hemicellulose, Lignin |

Table 2.1: Conditions of Fungal Growth: The minimum necessary requirements to allow and sustain fungal growth

of the mold.  Additionally external forces which hinder the growth of mold such as wood treatment and other biological organisms are taken into account.

# Chapter 3

# Mold Creation Process

## 3.1 Mold Creation Scheme

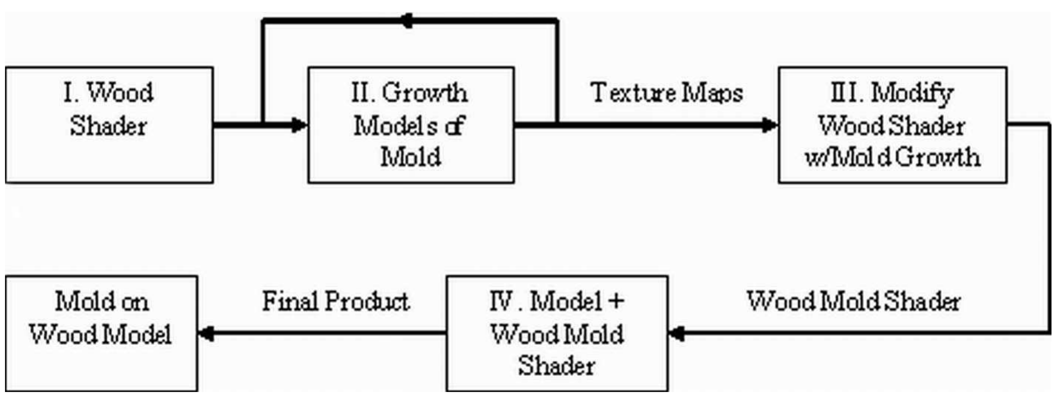



Figure 3.1: Procedural Overview. The boxes represent the significant steps of the rendering scheme. The output of one step, written above the arrows is the input of the next step.

The key component to creating our mold shader is to use a Renderman wood shader [21] as the starting point. Figure 3.1 shows the process that produces the mold shader that is applied to a model. The wood shader is unwrapped to create a texture map that is used by the growth models as input for step II. Given moisture concentration, mold growth rates, and the wood texture map, the growth model is able to make predictions as to where mold will grow. The wood mold texture maps that are produced by the growth model in step II are combined together and processed to create a physically comparable mold shader in step III. The mold shader is applied to the computer models to render a wood textured model with mold growth as shown in step IV.

## 3.2 Wood Shader

Using an existing wood shader, we parse the shader to extract the lighting parameters that characterize the wood. The wood shader is applied to a geometric model, such as a cube or sphere, that is similar in form to the final cut wood model used if the final model cannot be unwrapped. The model is unwrapped into texture space to create a texture map. The model is unwrapped using a displacement shader which can be found in Appendix B.1. The displacement shader translates the surface position to the window location of the image resolution. This location corresponds to the texture coordinate we have computed for the

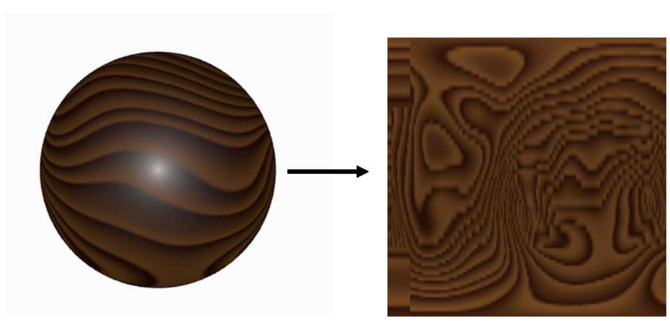


Figure 3.2: Transformation of a unit sphere with a wood shader into a wood texture map.

given resolution. Figure 3.2 shows the unwrapping of a unit sphere into a wood texture map. The texture map is used as input for the growth model to build upon.

The basis of our model unwrapping comes from the work on *pelting* by Piponi and Borshukov [12]. Pelting refers to the cutting and stretching of a model to assign texture coordinates to vertices. Once a model has been pelted, texture coordinates are assigned using planar projection. The vertices that were involved in the cutting process are assigned arbitrary texture coordinates. These texture coordinates are adjusted by blending overlapping pieces of the model surrounding the cut area. Piponoi and Borshukov are able to successfully create a texture map from a model without permanently modifying the model itself.

## 3.3 Modeling of Mold Growth

As mentioned previously in Section 2.5, there is no growth model of mold that has been widely accepted. For that reason, we use a generalized mold growth model that takes into account the life cycle of mold as shown in Figure 3.5 in addition to external forces. External forces play a part in the growth of mold by causing resistance and attempting to prevent the growth from occuring. An example of an external force is the treatment of wood causing a resistance in mold growth. The presence of biological organisms other than mold is an external force that may hamper or prevent growth. We account for the existence of these external forces within our generalized model. Outside of these forces, we assume the minimum conditions of mold growth are maintained despite the natural tendency for weather to fluctuate. The wood texture map is analyzed at each time step to see what stage

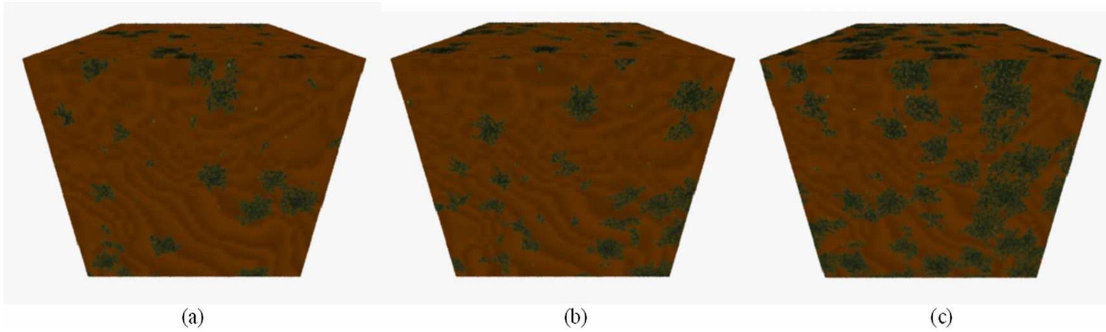



Figure 3.3: Mold growth in 3 areas with different moisture levels after 8 years as shown on a wooden post. (a) Illinois - Low Level Moisture. (b) Maryland - Medium Level Moisture. (c) Louisiana - High Level Moisture

of the life cycle a cell is experiencing. Since the growth of the mold takes place in texture space we account for the texel spacing in our model. We record the changes in age, growth height and growth spread in their own texture maps so that we may use them to produce the final image of the mold growth.

### 3.3.1 Environment

Oxygen and the presence of a food source are assumed to be plentiful in the areas where we model mold growth. The conditions of temperature and moisture cannot be as easily assumed. In the physical environment, the weather conditions in a given area are not necessarily the same as another. Table 3.1 shows the different temperatures and levels of rainfall that exist in different parts of the United States. We use rainfall data to determine the moisture content of a given area. It is necessary that both temperature and the degree of moisture of an area meet the conditions that were listed in Table 2.1. All of the states in Table 3.1 meet both of these conditions with the exception of Arizona which falls below the necessary 20% moisture concentration. The moisture degree of an area falls within a

| | Average Temperatures for 2004 | Average Rainfall for 2004 | Average Rainfall Percentage |
|---|---|---|---|
| Arizona | 84.33 | 0.69 | 9.85% |
| California | 70.75 | 2.12 | 30.28% |
| Illinois | 59.92 | 3.17 | 45.28% |
| Kansas | 65.83 | 3.60 | 51.43% |
| Maryland | 68.08 | 3.63 | 51.86% |
| Louisiana | 78.83 | 5.35 | 76.43% |

Table 3.1: Temperature ($^oF$) and Rainfall (inches) Data for States in the U.S. Rainfall calculations are used to determine the moisture content. Rainfall percentage is based upon an average of 7.00 inches. [23]

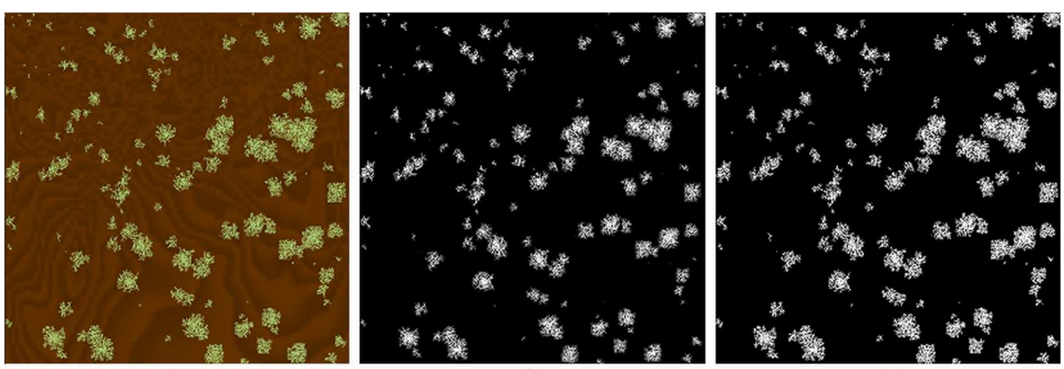
range which is used to describe the level of moisture that is associated with that area. A low level of moisture has a moisture range of 20% to 45%. Between 46% and 69% is a medium level moisture and an area with a moisture degree between 70% and 100% is said to have a high level of moisture. Figure 3.3 displays the difference in mold growth for areas with different environmental conditions after a period of five years. From the figure an increase in the presence of mold is shown as the moisture level increases. Since there are many rates of growth for different species of mold, we use a generalized surface growth rate of 0.1 inches/day (data provided by Dr. Jeffrey Morrell of Oregon State University [11]).

### 3.3.2 Texture Maps

The wood texture map that is used by the growth model is built upon for each time step. After the growth model has completed processing the wood texture map, it outputs a *mold texture map*. The mold texture map tells us the location of spore and hyphae growth that occurred during the allotted time.

Capturing the spread of the mold growth does not provide enough information to create a genuine appearance. With the passing of time, mold change their appearance and age. As spores and hyphae are created, their time of birth is recorded in a *life texture map*. The life texture map is used during the rendering process to determine an approximate age of the mold and develop it accordingly.

Mold is not restricted to growing solely along the surface. Mold can grow on top of itself increasing in height. We implement a *height field texture map* that tracks the growth of the mold above the surface which initially has a height of zero. The height of the mold grows with each passing day by the growth rate. Figure 3.4 shows the texture maps that were created by the growth model for a medium moisture area after four years. Given a location of mold in the mold texture map, the height and age of the mold can be found in the height field and life maps respectively. If no mold has been grown then that absence of growth will be shown in the height field and life maps by the color black with a value of zero.



(a) (b) (c)

Figure 3.4: Texture Maps after 4 years in Medium Moisture Area: (a) Mold Growth. (b) Mold Height Field. (c) Mold Life

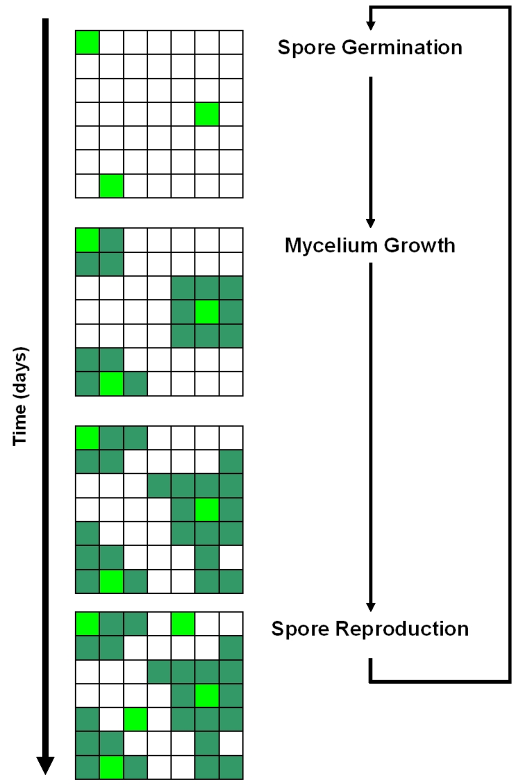



Figure 3.5: Life cycle of a spore. The status of moribund is not illustrated.

### 3.3.3 Growth of Spores and Hyphae

Our generalized method for modeling mold growth provides mold with the opportunity to undergo the stages of spore germination, mycelium growth, and sporulation. Figure 3.5 shows the process that the wood map undergoes. As time passes, each cell of the wood map has the opportunity to grow and age. The light green cells indicate spores, while the dark green cells show mycelium growth. Depending on the type of moisture environment, the frequency of sporulation varies. Areas with lower moisture levels take a longer time to sporulate and to produce hyphae in comparison to areas with medium or high level moisture. During the time of sporulation and hyphae production, not every wood cell will produce mold. We utilize a random number generator and probability to determine if a wood cell would become a spore or hyphae. These frequencies and probabilities are adjustable and are listed in Appendix A.1. To account for the texel spacing that occurs the probabilities are scaled by the distance of the position on the model and the position in the texture map. This calculated Euclidean distance is then multiplied by the listed probabilities to provide a more reflective probability in texture space

Each cell on the wood texture map has the potential for mold growth. We identify the cells by their stage identifier which can be wood, spore, hyphae, or other. If the stage of a cell is wood, then we know that no mold growth has occured. A spore or hyphae stage tells us that mold growth has begun. The other stage identifier informs us that an external factor such as another organism or the death of mold prevents mold growth from occuring in that cell. Figure 3.6 show the state diagram of a wood cell. Initially all cells will begin in a wood state and will move to its next state after being processed. If a cell is found to be affected by external factors then despite its current state it will move to an Other state. The transition of a Wood state to a Hyphae state is dependent upon its neighboring cells. A cell that becomes a Spore or Hyphae will remain in that state unless acted upon by external factors. When we mark or identify a cell as a spore or hyphae we mark the texture map with an initial mold growth color. Cells that are identified as either a spore or hyphae begin to grow outwards radially. The immediate neighbors of the cell are checked for potential growth and marked accordingly. Throughout the growth of the spore and hyphae, the height of the cells are incremented. The growth model algorithm shown in Figure 3.7 describes how the texture map is processed. After we have created the mold, height field, and life texture maps, they are passed to the mold shader for processing.

## 3.4 Rendering of the Mold

To use the information stored in each of the texture maps, we use a one-to-one mapping to align the points on the model with their respective texture coordinates for our simple cube model. We use a cube mapping to provide our uniform mapping. The complex head model consists of a one-to-one mapping and does not need an additional mapping. A sample of our cube mapping used for the height field texture map can be found in Appendix C.1. Using the mold texture map as the sole input for the mold shader would not truly reflect the mold appearance. The mold texture map alone would provide a one dimensional appearance that gives an artificial look. Physical mold has a surface inconsistency that needs to be accounted for in order to view the mold on wood properly.

The height field texture map is used in conjunction with a displacement shader to adapt the

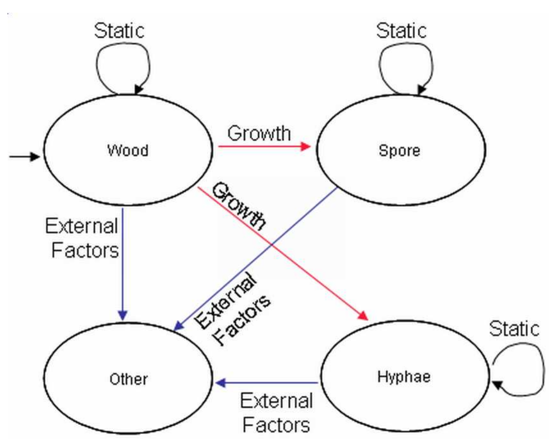



Figure 3.6: State Transition Diagram for Wood Cells

```
For each time step
    For each wood cell in the texture map
        Is this cell Wood?
            If yes
                Do External Factors claim the cell?
                    If yes
                        Mark external
                Is it time to Sporulate?
                    If yes
                        Is this cell a potential spore?
                            If yes & No External Factors
                                Mark as a spore
                                    Update height and age maps
                            If External Factors
                                Mark external
        Is this cell a Spore or Hyphae?
            If yes
                Is it time to Produce Hyphae?
                    If yes
                        Check immediate neighboring cells
                            Check External Factors for each cell
                                Is the neighboring cell a potential Hyphae?
                                    If yes & No External Factors
                                        Mark as hyphae
                                        Update height and age maps
                                    If External Factors
                                        Mark external
                Do External Factors claim the cell?
                    If yes
                        Mark external
Print texture maps
```

Figure 3.7: Pseudocode for the Growth Model

mold texture map. The height of each cell is added to the point on the surface of the model, thereby displacing the mold to its grown height. The displacement shader will visually represent the growth of the mold above the surface over time. Mold does not maintain a constant shade of a single color. As mold ages, the effects of time on the mold are reflected through the change in mold color. The ages contained in the life texture map have all been normalized and are checked against the age ranges of older years, middle age, and younger years. A mold color is associated with each age range and a spline is used to provide a continuous progression. Older years have a darker green mold color, middle age has a green mold color, and the younger years have a light green mold color. The color associated with each age cell is mixed with the initial mold color that was used to create the mold texture map. These age ranges and their respective colors are adjustable and can be found in Appendix A.1.

Most non-metallic materials have some degree of translucency, including wood. Light is both reflected and refracted by the wood surface. Some of the light that passes into the wood will scatter around inside before it is refracted. This tells us that subsurface scattering is occuring to some extent. For this reason we use 3Delight's direct implementation of the Jensen et al. subsurface scattering model [20]. We use the lighting parameters that were extracted during the unwrapping process of the wood shader. The lighting of the mold is adjusted according to the age of the mold to create an aged look.

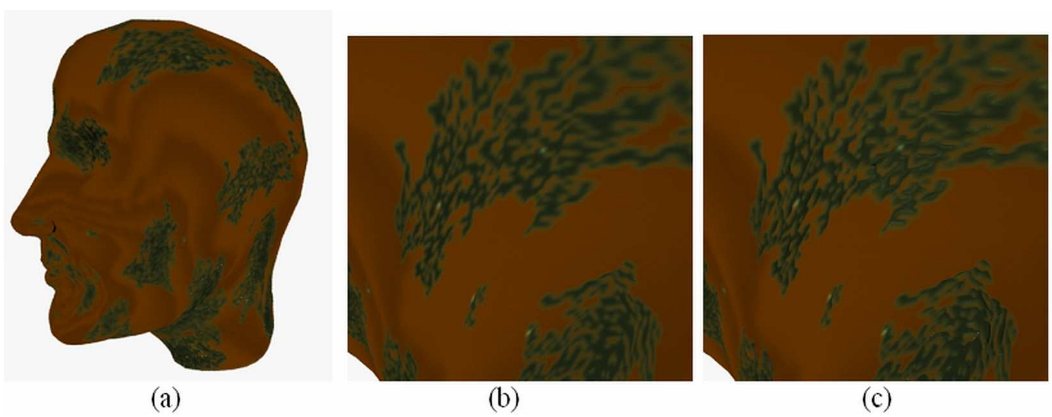



Figure 3.8: Mold growth on a wood head after 7 years in a low moisture environment. (a) Mold growth on wood head. (b) Close look at mold growth on wood head without height field applied. (b) Close look at mold growth on wood head with height field applied

The impact of the height field map is not seen from afar in Figure 3.8a. In Figures 3.8b and c we can see a distinct difference in the use of the height field map. Without the use of the height map in Figure 3.8b the mold growth has a flat one-dimensional appearance. In

Figure 3.8c we see the mold grow off of the surface.

Figure 3.9 shows the effect lighting and the life texture map have on the appearance of the mold. The lighting model highlights a key difference between wood and mold. Wood has more of a lustrous property in comparison to the mold. Mold absorbslight more than wood thus giving it a diffuse appearance.

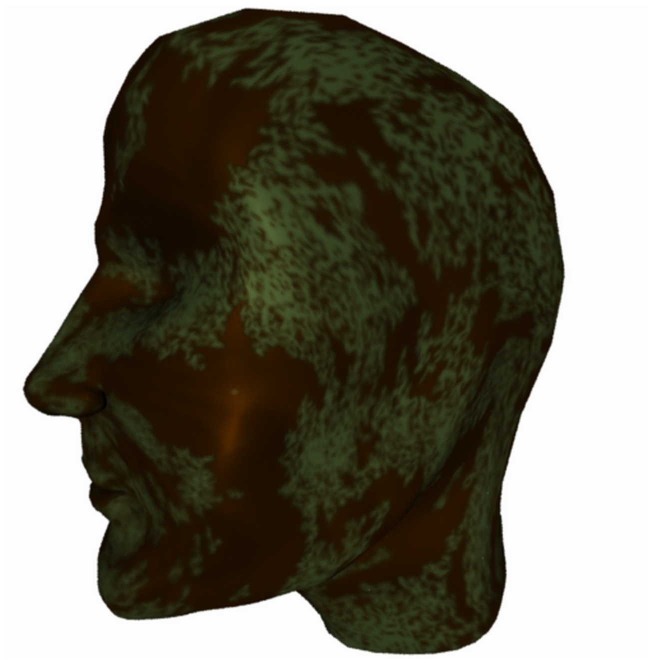


Figure 3.9: Mold growth on a wood table after 10 years in a high moisture environment. The lighting model takes part in showing the materialistic difference between mold and wood.

The progression of the growth of mold over a period of time is shown in Figure 3.10. The growth of the mold is captured during a nine year period in a medium moisture environment. Over this time we see the aging of the older mold and the growth of new mold.

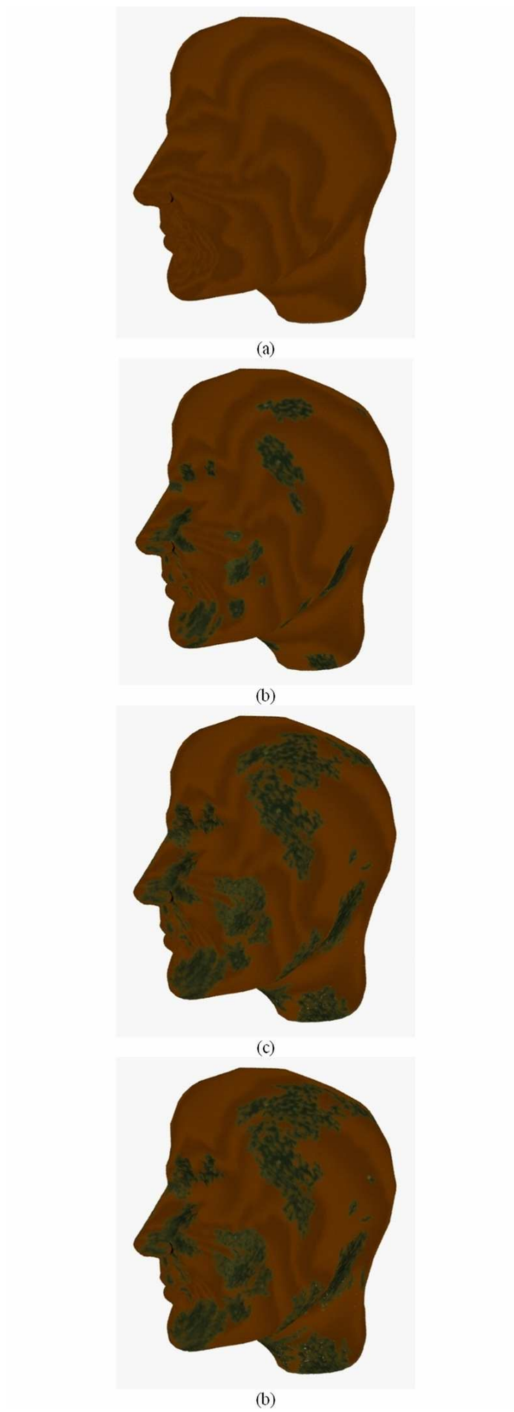



Figure 3.10: Mold growth on a wood head over a period of 9 year in a medium moisture environment. (a) Mold growth initially. (b) Mold growth at 3 years. (c) Mold growth at 6 years. (d) Mold growth at 9 years.

# Chapter 4

# Conclusion and Future Work

We have presented a system for modeling and rendering mold on cut wood. The main idea has been to build upon any arbitrary existing wood shader. Mold growth is simulated using the wood texture map created by the wood shader and passed through the growth model. Displacement mapping and subsurface scattering was applied to the mold growth to provide a sense of realism. The system can be applied to cut wood that is found in any area that meets the minimum requirements of temperature and moisture concentration.

The system of modeling and rendering allows for a graphics artist to have more control over factors that will affect the creation of the mold. The techniques used for creating the mold on wood can be applied to other materials that are known for attracting mold such as bread and other food. The growth model is a generalized version that can be applied to mold of different varieties. Specific growth rates can be given for particular type of fungus. The mold creation scheme can be further modified to accommodate the growth of other biological organisms such as moss.

# Appendix A

# Modifiable Variables

| Variable Type | Dimension |
|---|---|
| Frequency of Spore Sporulation - Low Moisture | 270 days |
| Frequency of Spore Sporulation - Medium Moisture | 220 days |
| Frequency of Spore Sporulation - High Moisture | 110 days |
| Frequency of Hyphae Production - Low Moisture | 90 days |
| Frequency of Hyphae Production - Medium Moisture | 85 days |
| Frequency of Hyphae Production - High Moisture | 75 days |
| Probability of Spore Development | 1 in 20 |
| Probability of Hyphae Formation | 1 in 10 |
| Probability of External Factors | 1 in 20 |
| Probability of Wood Treatment | 1 in 10 |
| Probability of Death | 1 in 5 |
| Older Years Range | 100 - 51 % |
| Middle Age Range | 50 - 26 % |
| Younger Years Range | 25 - 0 % |
| Initial Mold Color | {.656,.781,.445} |
| Older Years Color | {.085,.113,.046} |
| Middle Age Color | {.292,.464,.125} |
| Younger Years Color | {.414,.535,.211} |

Table A.1: Some Modifiable Variables Used in the Growth of Mold

# Appendix B

# Unwrapping Displacement Shader

# Source Code

```
#include "rmannotes.sl"

displacement unwrap (
     output varying point myP = 0;){

     myP = P;
     P = transform("camera","current",point(u*2.1 - 1.1, v*2 - 1, 1));
}
```

Figure B.1: Shader code for unwrapping the unit sphere into a texture map

# Appendix C

# Height Field Cube Mapping Source Code

```
displacement displaceP(float cubeS = 1;
                        string hmap="heightfield.tex";){
        float x = 0;
        float y = 0;
        float z = 0;
        float xP = 0;
        float yP = 0;
        float zP = 0;
        float tmpX = 0;
        float tmpY = 0;
        float tmpZ = 0;
        float i = 0;
        float j = 0;
        float mgn = 0;
        float dcube = 2 * cubeS;
        vector ref;
        point PP;

        PP = transform("object", P);
        normal Nf = faceforward( N, I);
        vector V = normalize(-I);

        ref = N;

        x = xcomp(ref);
        y = ycomp(ref);
        z = zcomp(ref);
        xP = xcomp(PP);
        yP = ycomp(PP);
        zP = zcomp(PP);

        if(xP > yP && xP > zP)
        {
                tmpY = yP + cubeS;
                tmpZ = zP + cubeS;
                i = tmpY / (2 * cubeS);
                j = tmpZ / (2 * cubeS);
        }

        if(yP > xP && yP > zP)
        {
                tmpX = xP + cubeS;
                tmpZ = zP + cubeS;
                i = tmpX / (2 * cubeS);
                j = tmpZ / (2 * cubeS);
        }

        if(zP > xP && zP > yP)
        {
                mgn = abs (z);
                tmpX = xP + cubeS;
                tmpY = yP + cubeS;
                i = tmpX /(2 * cubeS);
                j = tmpY /(2 * cubeS);
        }

        if(float texture(hmap, i, j) != 0){
                P = P + (float texture(hmap, i, j) * .010);      //height field
        }
        else{
                P = P;
        }
        N = calculatenormal(P);
}
```

Figure C.1: Shader code for uniform mapping of height field map

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