# SIMULATING PLANT COLOR AGING
# TAKING INTO ACCOUNT THE SAP FLOW IN THE VENATION

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## ABSTRACT

This paper presents a method for simulating color aging of leaves. Our technique is inspired by natural processes. We consider the flow of fluid in the leaf, and its evaporation through stomata. To model this, we use three maps describing the stomata and venation distributions and the fluid flow, respectively. We conduct a simulation that uses these maps to update the amount of fluid sourced into, diffused, and sinked out of the plant structure. The amount of fluid present at each location is used to control the color of the leaf or petal.

## 1 INTRODUCTION

Senescence is a process present in the vast majority of plants and animals. It provides important visual clues of the natural aging process, and is an important part of modeling ecosystems. Realistic modeling and simulation of ecosystems has applications in both the film industry, as well as in the video-games industry. Plants are a fundamental component of these ecosystems, and they are the focus of this paper. Our objective is to provide a mechanism that can be used to model the color evolution that plants suffer during their lifetime.

A considerable amount of work can be found on modeling the evolution of plants and trees [1, 2, 3]. However, these methods concentrate on the initial part of the plants development, until the organism reaches maturity. By comparison, the decaying part of the plants life is still left more or less unexplored.

During the senescent part of a plant life-cycle, it goes through a series of changes that are visually complex, including changes in shape, color and texture. These changes are significantly different from the growth animation process, and therefore require a specific simulation process. Our aim is to achieve more natural results in color aging simulation. In this paper we focus on leaf senescence, even though we also present an example using petals.

The venation and stomata have important roles in the leaves during their aging process. The venation has both a support and nutrient distribution roles. The nutrient distribution is made by the sap which also carries hormones, and water in the venation channels. These substances will diffuse in the cells throughout the leaf. The nutrients are then consumed by the cells, and the water will evaporate from the stomata. Thus, simulating the sap flow in the plant structures is important for reproducing the biological process occurring naturally in the plant. Therefore, in this paper we present a technique to simulate this sap flow.

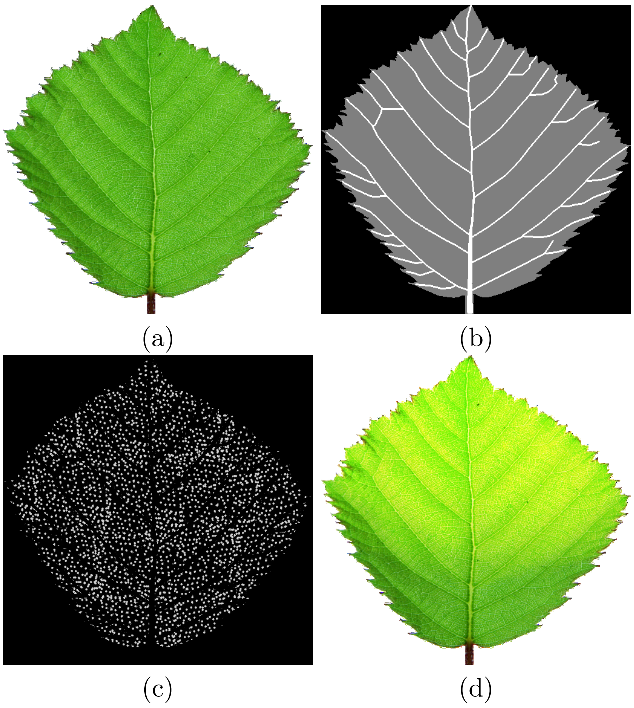


Figure 1: (a) input leaf, (b) venation map (c) stomata map, and (d) simulation result.

Our method takes as input a venation map, containing the veins of the leaf or petal, and a stomata map representing the distribution of the stomata on the surface. A fluid map, representing the sap flow, is generated automatically and records the time evolution of the simulation. We apply this sap flow simulation to the generation of color changes that the plant suffers during its growth and senescent phases.

## 2 RELATED WORK

This research closely relates to two kinds of work in plant modeling. Works on modeling the early stages of the plant life, and works modeling the senescent period of the plant life. We shortly present relevant related work in both areas.

### 2.1 Growing Plants

One of the oldest examples of plant evolution animation is the work by Prusinkiewicz et al. [1]. This method is based on an L-system-like productions and differential equations, and can produce time-lapse like animations of the plant evolution from sprout to blossom. Another work on blossoms was presented by Yao et al. [4]. This work uses a predefined function for the angle and scaling of the petals of the modeled flowers. However these methods do no support plant senescence simulation.

### 2.2 Senescence Simulation

Hong et al. [5] and Lu et al. [6] both presented methods to animate leaf deformation, which could possibly be used to animate leaf senescence. However, both these methods focus on animation so color change must be made manually.

Peyrat et al. [7] presented a method based on L-systems, which is capable of generating shapes and textures of leaves for their entire life cycle. However this method requires the creation of a grammar to obtain a desired result. This not only makes it hard to use, but the provided results also show patterns which might look unnatural.

Desbenoit et al. [8] presented a method for modeling autumn leaves. They simulate the aging related coloring changes by using a series of template input images, and associating them to states which are attained by progressing in a Markov Chain. This forces the user to obtain a great number of input textures in order to produce a diversified result.

Abe et al. [9] presented a technique for simulating scenes with falling autumn leaves. In their implementation, the process leading to the leaves falling is controlled by a simulation based on the plant physiology. The factors considered are the hormonal content in the leaves. The main difference to our method is that we aim to obtain a more detailed result, by considering the natural phenomena at a smaller scale over the leaf surface.

## 3 OUR METHOD

Our objective is to simulate the color evolution in leaves. For this we consider that each leaf or petal is represented by a geometry and a possibly individual color map. An example of a color map can be seen in Fig. 1 (a). Our objective is to change that color from its initial value to a value that would be plausible by natural aging.

For this we consider the natural processes occurring in the plant, like the flow of hormones, nutrients, and water into and out of the leaf. For the input flow we use a texture, which we call venation map, that represents the fluidity at each point in the leaf. An example of a venation map can be seen in Fig. 1 (b). Each pixel in this map represent how easy the fluid flows in that region. White values represent more flow capacity, and as the pixels get darker it represents less flow capacity. We use a diffusion process to simulate the flow in the venation. We believe the venation map can be created using methods such as [5, 10], but for the purpose of the examples presented in this paper the corresponding venation maps were manually generated.

We also consider the evaporation as a form of extracting the fluid out of the leaf. For this outward flow we use a stomata map. This is a texture map that contains the distribution of the stomata over a region. An example of a stomata map can be seen in Fig. 1 (c). Each pixel in this map represent how easy the fluid flows out of that region. Like the venation map, white means more transpiration and it goes down as the color gets darker. This model is not biologically exact, since the stomata tends to close when the plant becomes senescent [11, 12]. However we found this model suits our purposes, and a truly biologically correct model is left for future work.

### 3.1 Fluid Diffusion

To simulate the flow of fluid in the leaf we use a diffusion process which is described by Eq. (1).

$$\frac{\partial y(u,v)}{\partial t} = \nabla\cdot(\beta(u,v)\nabla y(u,v)) + I(u,v) - O(u,v), \quad (1)$$

where $y(u,v)$ is our fluid map, and $\beta(u,v)$ is our venation map, $I(u,v)$ represents the locations where the fluid enters the system, and $O(u,v)$ represents the stomata map. These are all two dimensional maps with coordinates $(u,v)$. We separate our simulation into a transpiration step, an inflow step and a diffusion step. The transpiration step is modeled by subtracting $O(u,v)$ from the fluid map $y(u,v) = y(u,v) - O(u,v)$. Then we have an inflow step, where we sum the contribution of $I(u,v)$ into the current fluid map $y(u,v) =$

$y(u,v)+I(u,v)$. For the diffusion process we temporarily ignore the contributions of $I(u,v)$ and $O(u,v)$ and focus solely on the remaining terms.

Similarly to the work by Kass et al. [13], we discretize by columns and then rows separately. This can be thought as making $v$ constant and discretizing for $u$, and analogously making $u$ constant and discretizing for $v$. This way, solving the two dimensional case is reduced to applying the one dimensional solution to the columns followed by applying it to the rows. The one dimensional dicretization can be denoted by Eq. (2).

$$y_i^{m+1} - y_i^m \approx \beta_i(y_{i+1}^{m+1} - y_i^{m+1}) - \beta_{i-1}(y_i^{m+1} - y_{i-1}^{m+1}), \tag{2}$$

where $y_i^{m+1}$ is the $i$-th pixel of the fluid map at time step $m+1$. The $i$ index alternates between columns and rows. Similarly, $y_i^m$ is the $i$-th pixel of the fluid map computed in the previous step. By solving for $y_i^m$ we get Eq. (3).

$$-\beta_{i-1}y_{i-1}^{m+1} + (\beta_{i-1}+\beta_i+1)y_i^{m+1} - \beta_i y_{i+1}^{m+1} = y_i^m. \tag{3}$$

As implicit in Eq. (3), we have a system represented by Eq. (4), also known as the backward Euler method.

$$A\mathbf{y}^{m+1} = \mathbf{y}^m. \tag{4}$$

This requires us to invert the matrix $A$. We solve the system $A$ by Crout factorization [14], where each column of the fluid map is solved by back and forward substitution. Then this result is used as $\mathbf{y}^m$ and the solving process repeats for the rows. The values in the tridiagonal system $A$ correspond to values of a column or row of the venation map. This correspondence is given by the relation defined in Eq. (5).

$$\begin{cases} a_i = -\beta_{i-1} \\ b_i = \beta_{i-1} + \beta_i + 1 \\ c_i = -\beta_i \end{cases} . \tag{5}$$

This can be encoded into a linear system like the one defined by Eq. (6).

$$\begin{bmatrix} b_1 & c_1 & 0 & \cdots & 0 \\ a_2 & b_2 & c_2 & 0 & \vdots \\ 0 & a_3 & b_3 & c_3 & 0 \\ \vdots & & & \ddots & \vdots \\ 0 & \cdots & 0 & a_n & b_n \end{bmatrix} \begin{bmatrix} y_1^{m+1} \\ y_2^{m+1} \\ y_3^{m+1} \\ \vdots \\ y_n^{m+1} \end{bmatrix} = \begin{bmatrix} y_1^m \\ y_2^m \\ y_3^m \\ \vdots \\ y_n^m \end{bmatrix} . \tag{6}$$

The fluid map initial state $t = 0$ can be anything including a state loaded from an external resource like an image. We consider that nothing comes in or gets out of out fluid map at the boundaries. This is equivalent to using the conditions defined in Eq. (7).

$$\begin{cases} b_1 = \beta_i + 1 \\ b_n = \beta_{i-1} + 1 \end{cases} . \tag{7}$$

### 3.2 Color Calculation

To create the senescent color image we use a sample image of a senescent leaf as reference and perform histogram matching. Note that the reference image can be anything. It can differ from image that we wish to change in both size and contents. But since we want to mimic the color of a senescent leaf, it helps if the reference image content is an example of the desired color. For the sake of clarity we explain shortly the histogram matching method [15]. This method takes a reference image for which we calculate the histogram $H_{ref}(n)$, where $n$ is a gray-scale value of one color channel. We do this for each of the reference image color channels. Then from this histogram we calculate the corresponding cumulative distribution function $cdf_{ref}(n)$ given by Eq. (8).

$$cdf(n) = \frac{\sum_{i=0}^{n} H(i)}{\sum_{i=0}^{N} H(i)}, \tag{8}$$

where $N$ is the size of the histogram. We do this again for the input image, to which we will call $H_{src}(n)$ and $cdf_{src}(n)$. From this we can compute a mapping from a value from the input image to a value from the reference image using Eq. (9).

$$n' = cdf_{ref}^{-1}(cdf_{src}(n)), \tag{9}$$

where $n$ is a gray-scale value of the input image, and $n'$ is the resulting gray-scale value in reference image. This allows us to automatically compute a senescent color, although it is just an approximation of the actual color. Although other methods like [16, 17] might possibly achieve better results in certain situations, we found this method to provide good results for our objectives.

## 4 RESULTS

In this section we present some results obtained with our system, and the correspondent simulation data.

### 4.1 Example Animations

For these tests the venation and the stomata maps were built by hand, using an image editing software. Their automatic generation is left as future work. In Fig. 2 we show a sequence of fluid propagating and the corresponding sequence of color changes as the fluid amount changes. We believe this result to be comparable with the actual phenomena. One such result can be found in [18]. More examples can be seen in Fig. 3, where we show an animation sequence for a flower, and Fig. 4 where we show a fig leaf example. The flower example

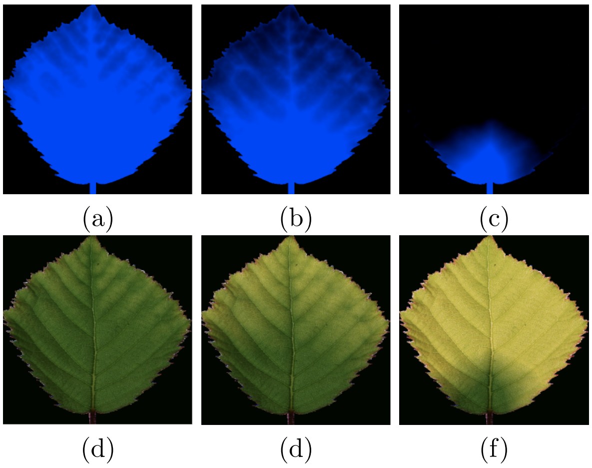

(a) (b) (c)
(d) (d) (f)

Figure 2: Above, example of a fluid diffusion sequence for a bramble leaf (a), (b), and (c) at time $t = 0$, $t = T$ and $t = 2T$. Below, the corresponding color changes (d), (e), and (f).

aims to demonstrate that our method can target not only leafs but also other similar structures like petals.

Many distributions can be used, some for more artistic results, other for more natural results. Some examples of how different stomata maps influence the simulation can be seen in Fig. 5. The examples Fig. 5 (a), (b) and (c) correspond to a uniform stomata distribution, and the results Fig. 5 (d), (e) and (f) correspond what could be an artist designed stomata map.

### 4.2 Performance

Our tests were conducted on a laptop equipped with an *Intel Core 2 Duo* CPU running at $2.13GHz$, $2GB$ main memory, and a *NVIDIA GeForce 9400M* GPU with $256MB$ of dedicated video memory. The size of the textures used were at most $512 \times 512$. Under our currently non-optimized implementation we can still achieve easily real-time performance taking hundreds of simulation iterations per second.

The timing values summarized in Tbl. 1 correspond to the average amount of milliseconds per time step for each of the examples presented in this paper. Our simulation takes just a few seconds in order to transition from the original image to the senescent image. Note that this could be accelerated or decelerated depending on the input maps. Using values in the interval $[0, 1]$ for venation and stomata maps, and values 1 pixel for the spatial change and 1 for the temporal change, will result in a transition that takes just a couple of seconds. Decreasing the values in the stomata map, will result in an animation longer, and possibly different, and it allows more time for the input flow to diffuse and counter the evaporation effect.

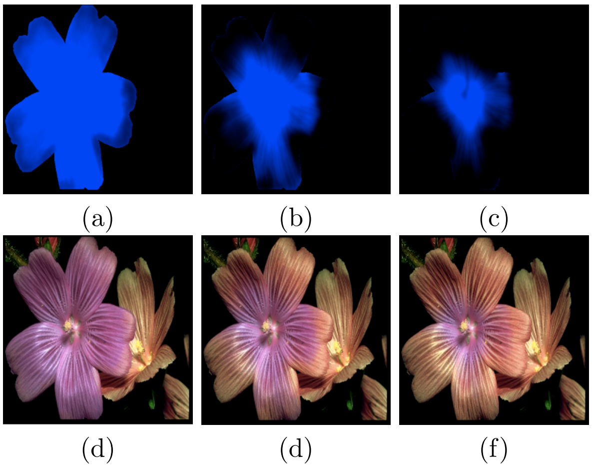

(a) (b) (c)
(d) (d) (f)

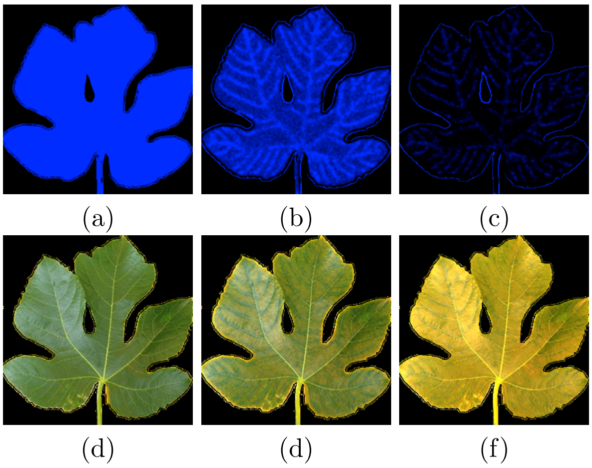
Figure 3: Above, example of a fluid diffusion sequence for a flower (a), (b), and (c) at time $t = 0$, $t = T$ and $t = 2T$. Below, the corresponding color changes (d), (e), and (f).

Table 1: Performance evaluation. Milliseconds per simulation step.

| Name | 128 × 128 | 256 × 256 |
|---|---|---|
| Bramble | 2 | 9 |
| Fig | 2 | 8 |
| Flower | 1 | 6 |
| Name | 512 × 512 | 1024 × 1024 |
| Bramble | 35 | 174 |
| Fig | 29 | 149 |
| Flower | 25 | 118 |

### 4.3 Limitations

Given these values we can state that a small plant, composed of several individual leaves would be simulated in a similar amount of time. Instantiation might be useful for plants or trees composed of a great amount of individual leaves. However a limitation of this method is in the prepossessing necessary to detect the individual plant parts, and generate the necessary data structures, might not be possible if the object is complex and has self occlusions. This would not be a problem for objects that are procedurally generated or with individually modeled components. Another limitation is in the range of plants to which we believe this method can be applied. This method is mainly aimed at angiospermic plants, since those have leafs with visible venation, which is important the creation of the necessary data


(a) (b) (c)

(d) (d) (f)

Figure 4: Above, example of a fluid diffusion sequence for a fig leaf (a), (b), and (c) at time $t = 0$, $t = T$ and $t = 2T$. Below, the corresponding color changes (d), (e), and (f).

structures.

## 5 CONCLUSION AND FUTURE WORK

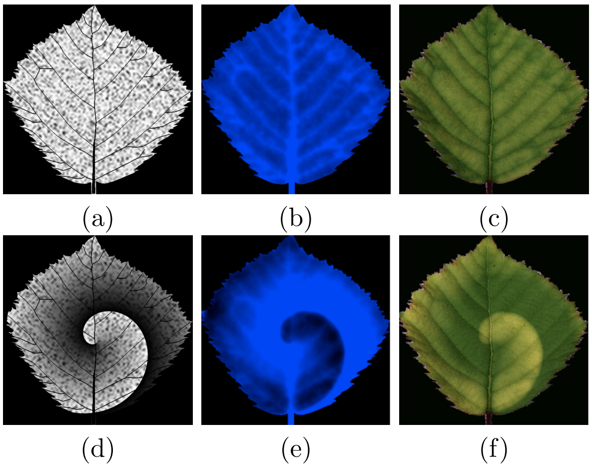
We presented a method to control the color changes in a plant while it decays. In this paper we limited our applications to controlling color in the aging process. However we think our simulation can also be extended to control the structure of the plant. As mentioned previously, the venation also has a structure support purpose. Because of this, we believe that the hydraulic pressure can be used as a variable to control the shape of the plant in a complete aging simulation. As a future work we aim to simulate structural changes, like the blossom and shrinking of certain plant structures. With this we aim to create a system to automatically generate meshes of plants and the corresponding animations of senescence, all from a single input photo.

## REFERENCES

[1] P. Prusinkiewicz, M. S. Hammel, and E. Mjolsness, "Animation of plant development," SIGGRAPH '93, pp. 351–360, 1993.

[2] J. Weber and J. Penn, "Creation and rendering of realistic trees," SIGGRAPH '95, pp. 119–128, 1995.

[3] M. T. Wong, D. E. Zongker, and D. H. Salesin, "Computer-generated floral ornament," SIGGRAPH '98, pp. 423–434, 1998.


(a) (b) (c)

(d) (e) (f)

Figure 5: Different examples of stomata maps (a), (d), fluid maps at some time $T = \tau$ (b), (e) and the corresponding color results (c) and (f).

[4] J. Yao, X. Xie, M. Zhang, H. Zhang, and A. J. A. Wang, "A 3-d flowering simulation based on botany characteristics and random generation algorithm," in *ACM SIGGRAPH 2010 Posters*, 2010.

[5] S. M. Hong, B. Simpson, and G. V. G. Baranoski, "Interactive venation-based leaf shape modeling: Natural phenomena and special effects," *Comput. Animat. Virtual Worlds*, vol. 16, no. 3-4, pp. 415–427, 2005.

[6] S. Lu, C. Zhao, and X. Guo, "Venation skeleton-based modeling plant leaf wilting," *Int. J. Comput. Games Technol.*, vol. 2009, pp. 1:1–1:8, 2009.

[7] A. Peyrat, O. Terraz, S. Merillou, and E. Galin, "Generating Vast Varieties of Realistic Leaves with Parametric 2Gmaps L-Systems," *The visual Computer*, vol. 28, no. 7-9, pp. 807–816, 2008.

[8] B. Desbenoit, E. Galin, S. Akkouche, and J. Grosjean, "Modeling Autumn Sceneries," in *Eurographics 2006, short Papers.*, 2006.

[9] K. Abe, K. Itoh, and T. Kikuchi, "Procedural techniques for animating falling leaves for outdoor scenes," *IASDR*, pp. 1019–1026, 2006.

[10] A. Runions, M. Fuhrer, B. Lane, P. Federl, A.-G. Rolland-Lagan, and P. Prusinkiewicz, "Modeling and visualization of leaf venation patterns," *ACM Trans. Graph.*, vol. 24, pp. 702–711, 2005.

[11] K. V. Thimann and S. O. Salter, "Relation between senescence and stomatal opening: Senes-

cence in darkness," Proc. Natl. Acad. Sci. USA, pp. 2770–2773, 1979.

[12] K. V. Thimann and S. O. Salter, "Relation between leaf senescence and stomatal closure: Senescence in light," Proc. Natl. Acad. Sci. USA, pp. 2295–2298, 1979.

[13] M. Kass, A. Lefohn, and J. Owens, "Interactive depth of field using simulated diffusion," tech. rep., Pixar Animation Studios, 2006.

[14] R. L. Burden and J. D. Faires, *Numerical Analysis - 7th ed. ISBN 0-534-38216-9*, p. 408. 2001.

[15] J. P. Rolland, V. Vo, B. Bloss, and C. K. Abbey, "Fast algorithms for histogram matching: Application to texture synthesis.," *J. Electronic Imaging*, vol. 9, pp. 39–45, 2000.

[16] E. Reinhard, M. Ashikhmin, B. Gooch, and P. Shirley, "Color transfer between images," *IEEE Comput. Graph. Appl.*, vol. 21, pp. 34–41, Sept. 2001.

[17] T. Pouli and E. Reinhard, "Progressive color transfer for images of arbitrary dynamic range," *Computers & Graphics*, vol. 35, no. 1, pp. 67–80, 2011.

[18] P. O. Lim, H. J. Kim, and H. Gil Nam, "Leaf senescence," *Annual Review of Plant Biology*, vol. 58, no. 1, pp. 115–136, 2007.