

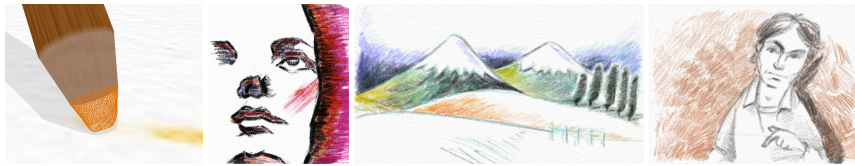
From Dust till Drawn

A Real-time Bidirectional Pastel Simulation

William Van Haevre, Tom Van Laerhoven, Fabian Di Fiore, Frank Van Reeth

Hasselt University
Expertise Centre for Digital Media
transnationale Universiteit Limburg
Wetenschapspark, 2
BE-3590 Diepenbeek (Belgium)
e-mail: william.vanhaevre@uhasselt.be

The date of receipt and acceptance will be inserted by the editor



Abstract We present a system for drawing pastel media in real-time as an effective alternative to most existing digital solutions that basically allow for drawing arbitrary strokes in a particular style. Our approach is focused on the simulation of the natural material itself and on its interaction with the drawing surface and the drawing tool.

Upon free-form drawing, a bidirectional transfer of pigment takes place. In one direction, the paper surface is dusted with new pigment particles broken off the tip (i.e. the end of the drawing tool). A large part of these particles will be deposited or blended together with previously deposited ones whereas the remainder does not contribute to the drawing and is blown off. On the other hand, a certain amount of previously deposited pigment is scraped off and picked up again soiling the tip. This is noticeable in the next strokes to be drawn. Furthermore, both the tip and the paper surface are subject to weathering depending on the exerted pressure and friction of the drawing tool, and the bumpiness of the paper. As a result, the paper surface slightly gets damaged limiting the deposition of new pigment. The tip, on the other hand, becomes blunt making new strokes wider.

From a stylistic point of view, similar to traditional drawings our results convey the artists' characteristics (e.g., way of wielding the brush, skillfulness, feeling for the medium). Therefore, we believe our system allows an artist to create realistically looking pastel images without losing his/her personal touch.

Key words I.3.4 [Graphics Utilities] Paint Systems – I.3.6 [Methodology and Techniques] Interaction Techniques – I.3.M [Miscellaneous] Highly-stylized Drawn Images

1 Introduction

Motivation. Since the 16th century pastels have been very popular in artistic communities, particularly for portrait painting and with this granting it a high-culture status. Nowadays, pastel media have gained a fashion status as well (e.g., in modern art) due to the medium's broad range of vivid colors. Consequently, pastel simulation has become an important feature of the set of natural art tools that are supported by digital paint software.

Existing digital paint methods, however, basically allow for drawing arbitrary strokes in a particular (painterly) style. And although very popular and appearing stylistic, many drawbacks are involved. Suitable interaction is needed between the paper surface and the drawing tools in order to effectively regenerate the strokes. A natural interaction model is also necessary instead of carefully setting numerous parameters to produce realistic results. Furthermore, complicated simulation requires considerable processing time in some cases, making it difficult to draw in real-time.

Moreover, the stylistic possibilities afforded by traditional drawing can be rich in a way which is seldom achieved by existing digital paint methods (even with significantly more effort). This becomes even more apparent when several artists, independent of each other, are asked to draw the same image once on paper and once using a digital tool. From a stylistic point of view, the digital versions nearly will look the same conveying the peculiarities of the software, contrary to the traditional ones which convey the artists' characteristics and hence will be perceived dissimilar from each other.

It is our objective to tackle these issues while keeping the artist in full control of the stylized drawing process.

Contribution. In this paper we present a system for simulating pastel media which is focused on the simulation of the natural material itself and its interaction with the drawing media (paper model and pastel stick/pencil).

Our approach primarily is based on a physically-inspired model, featuring the following characteristics:

- real-time free-form drawing tool to simulate pastel pigment depositions;
- bidirectional transfer of pigment (from the brush to the paper surface and vice versa);
- weathering of the tip and the paper surface;

- support for a wide range of pastel media (soft pastels, hard pastels, and pastel pencils).

The system's parameters are directly configured by (i) the artist's personal way of wielding the brush (e.g., pressure, orientation), and (ii) physical features of the drawing material (e.g., concentration of the binder, paper strength, stickiness of the pigment).

We believe our system allows an artist to draw realistically looking pastel images while bearing his/her personal creativity in mind. Examples are shown in the inset.

Approach. Pastel is an art medium in the form of a stick or pencil, consisting of pure powdered pigment and a binder. A pastel (drawing) is made by letting the sticks/pencils move over an abrasive surface, leaving color on the grain of the drawing medium [4].

Technically, the challenge is to achieve a bidirectional transfer of pigment when drawing strokes. To this end, pigment is deposited or blended upon contact with the paper surface while a certain amount of previously deposited pigment is picked up again. At the same time, we also take into account the occurrence of weathering due to the exerted pressure and friction. As a result the drawing surface slightly gets 'damaged' whereas the pencil's tip gets worn off.

Paper Organization. This paper is structured as follows. Section 2 surveys work we consider related to ours. Section 3 describes the important factors to be considered in order to draw or simulate pastel drawings. The actual simulation is elucidated in Section 4 whereas some examples are shown in Section 5. Finally, Section 6 is our conclusions section in which we also discuss our results and set the context for future work.

2 Related Work

It is fair to say that our work intrudes into the area generally known as Non-photorealistic Rendering (NPR) [1, 10, 7]. NPR techniques can be classified from interactive to fully automatic starting from different kinds of input including 3D geometries, images and brush strokes. As we are interested in real-time free-form pastel drawing, we limit our discussion to the NPR subcategory of stylized depiction by means of interactive brush strokes.

In 2003, Rudolf et al. presented a method for simulating wax crayons based on a physically-inspired model in which drawings are created in an interactive manner using user-defined strokes as drawing primitives [8]. Crayons are represented as dynamic 2D masks and upon contact between crayon and paper, wax is deposited according to the crayon's stroke contact profile and friction, possibly smearing previously deposited wax. The paper surface is represented by a generated height field texture, and a simplified Kubelka-Monk model [3] is employed to render the wax. More recently, Rudolf et al. extended their previous work by allowing deposited wax to be carved from the paper by the crayon in order to be

redeposited at another location [9].

The physically-inspired model and interactive nature of the system make it easy to generate images resembling crayon drawings. However, the current model is not fast enough for real-time rendering: it takes up to two seconds for rendering one stroke. Furthermore, several physical properties are not supported by the model including flattening of the paper surface due to friction and more complex smearing (i.e. not limited to only the neighboring cells).

Very recently, Murakami et al. generated realistic drawing strokes that simulate pigment depositions like charcoals, pastels, and crayons [5,6]. They primarily focus on the similarity between textures appearing on illuminated paper surfaces and pigments deposited on a paper surface by drawing a stroke. First, 12 paper textures with shading are captured/photographed from a paper surface which is illuminated from 12 directions by turning it every 30 degrees. Next, these textures are corrected and defined as a height field. When drawing a stroke, instead of calculating the interaction between each pigment and the paper, a height field is used consisting of the converted paper texture illuminated by a light coming from the same direction as the stroke.

By using the paper texture instead of simulating the deposition of pigments, strokes can be rendered in real-time. However, several issues remain with regard to real crayon drawings. It is nearly impracticable to smudge previously deposited pigment and the simulation does not take into account the orientation and wearing of the crayon's tip. Furthermore, similarity of regenerated strokes and real strokes is highly affected by the incident angle of illumination during the capturing process.

To sum up, existing NPR techniques deliver appealing results. However, contrary to our objectives, they do not completely take into account the artists' skillfulness or the physical properties of the drawing materials. As a consequence, this constrains the artist to express his/her creativity.

3 Pastel Drawing

The artist strongly has to bear in mind the different possible interaction factors that may occur when moving the sticks or pencils over an abrasive surface [2,4]. These factors will be discussed in the following subsections.

3.1 Drawing Factors

Unlike paints, pastels are not mixed before putting them on the paper. Instead, there are two ways to create color and tonal variations: (i) *optical blending*, which is achieved by having colors in close proximity (e.g., hatching), and (ii) *blending*, where the pastel is mixed on the paper.

Another important factor is the way the artist wields the pencil. The simplest way to use a pastel is to draw with the end, holding it as one would a pencil or pen. However, the final shape and color of each stroke are heavily related to the artist's personal style of working. For instance, by varying the pressure the thickness of the line can be altered; using the side of a pastel stick allows for creating large

blocks of color; by scumbling a pastel over the top of an existing block of color, pigment can be mixed; by scraping the stick's surface, dust can be created that can be pressed into the surface using a flat palette knife; . . .

In addition, we need to consider some important features of the drawing material as well. These features include the concentration of the binder, the strength of the paper and the stickiness of the powdered pigment.

3.2 Bidirectional Transfer of Pigment

While drawing using pastel, two transfers of pigment occur: (i) the deposition of new pigment from the pencil to the paper surface, and (ii) scraping previously deposited pigment off the paper surface. Regarding the latter, part of the scraped pigment will stick to the pencil, soiling its tip and influencing the next set of strokes to be drawn. The dusty remainder, however, does not contribute any further to the drawing and, in practice, is blown off the paper surface by the artist.

This bidirectional transfer is also affected by the way strokes are drawn, as discussed in previous subsection.

3.3 Weathering

As pigment is deposited on the paper surface, a similar volume will be worn from the tip. This decrease happens as one goes along and depends on the current shape and orientation of the tip.

In addition, each contact between the pencil and the paper slightly damages the paper surface. That is, due to exerting pressure little grooves are cut in the surface, which restrain a further deposition of pigment.

4 Simulation

Providing immediate visual feedback of the canvas and pencil interaction is essential in a free-form drawing application, while realistic simulation of the complex pastel behavior ensures convincing results. Previous attempts reported in literature have indicated that it is not an easy task to perform the computational intensive calculations while maintaining real-time simulation rates.

For this reason, we rely on programmable graphics hardware regarding all aspects of the simulation. The parallel nature of the GPU, in combination with texture objects to store the data, make the GPU a suitable candidate for guaranteeing an interactive application.

In the next subsections we first discuss the models that are used to represent the canvas and the pastel, followed by an in-depth description of the simulation pipeline.

Texture purpose	Content
Pastel tip (height field)	$[h_{\text{pastel}}, d_{\text{deformation}}, \text{unused}, \text{unused}]$
Attached pigments	$[p_1, p_2, p_3, p_4]$
Deposited pigments	$[p_1, p_2, p_3, p_4]$
Transferred pigments	$[p_1, p_2, p_3, p_4]$
Canvas (height field)	$[h_{\text{canvas}}, \text{unused}, \text{unused}, \text{unused}]$

Table 1 The different kinds of textures used in our simulation.

4.1 Canvas Model

The canvas model is built of two layers, each representing different aspects of the canvas.

Paper Layer. The structure of the canvas, the paper layer, greatly affects the way pigment is deposited onto its surface. A rough surface, for example, will result in fast weathering of the tip and vice versa.

In our system, the canvas structure is represented as a height field stored in a 2D floating point texture object (see Table 1). The source of such a paper-like structure can either come from digitizing a real paper sample (e.g., Murakami et al. [5]), or from an algorithm that creates a procedural texture (e.g., Worley [11]). Both of these are supported in our application. In addition, a per-pixel bump mapping technique is adopted to visualize the canvas.

Pigment Layer. A second layer, the pigment layer, captures all pigment quantities that have settled in the canvas’ surface irregularities. Floating point texture objects are used to track a mixture of different pigment amounts (see Table 1). The pigment layer is rendered by means of a real-time, GPU accelerated implementation of the Kubelka-Munk diffuse reflectance model [3]. Rather than using RGB values, this color mixing scheme describes each pigment’s appearance in terms of absorption and scattering parameters, and is able to composite a stack of pigment layers.

4.2 Pastel Model

The tip of the pastel is represented by a stack of float textures. The first texture lays out the shape of the tip, while the others store the amounts of different attached pigments. The resolution of these textures reflects the precision of the simulation. Experimentally a resolution of 32×32 was chosen for a 3mm wide tip. Figure 1 illustrates how the combination of such a set of textures can be interpreted to represent an actual pencil model.

Texture 1: Shape of the Tip. The shape of the tip is represented by a rectangular height field of which each texel stores the height of a single tip sample. As a result, only one channel of the texture needs to be addressed. In order to visualize the tip,

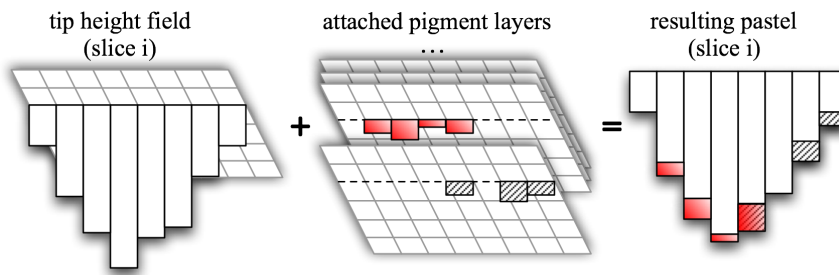


Figure 1 The pastel tip model (only slice i depicted for clarity): (left) row i from the tip height field; (middle) attached pigments for this row, one layer for each active pigment, four layers combined in one texture; (right) the resulting slice of the tip model.

a vertex shader is employed which, given the pencil's position and orientation, draws a set of 4 neighboring vertices as a quad, taking into account the height stored at each sample.

Textures 2..n: Attached Pigments. While drawing, a mixture of previously deposited pigment is scraped off the pigment layer and remains sticking to the tip.

For each different kind of pigment, being part of this mixture, one channel is needed to store the pigment data and, hence, one texture can store up to 4 different pigments. Consequently, given n textures, each tuple of n corresponding texels describes a mixture of $4 * n$ pigments sticking to a sample of the tip.

4.3 Simulation Pipeline

While interactively drawing strokes on the canvas, the pencil's trajectory is determined by linearly interpolating between each input position. At each interpolated position, the simulation steps shown in Figure 2 are executed. For this, we rely entirely on programmable graphics hardware.

The full simulation pipeline combines a sequence of different special purpose shaders, where the output of each shader is employed as input for the next. Figure 2 visualizes the pipeline and illustrates the different steps required to process each contact between the pastel and paper. The following steps are walked through in this pipeline:

1. Compute the projected footprint of the pastel tip on the paper surface.
2. Decide for each sample of the projected footprint whether it belongs to the actual area of contact, and if so, the amount of pigment breaking off.
3. Compute a net transfer of pigment based on the amount of pigment scraped from the pigment layer and the pigment volume removed from the tip.
4. Update the attached pigment mixtures according to these transfer rates.
5. Update the pigment layer.
6. Update the height field of the canvas, taking into account the drawing pressure.

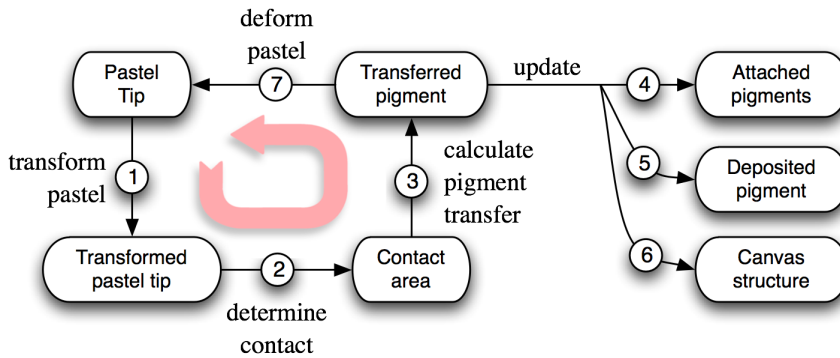


Figure 2 The simulation pipeline: 1) Calculate the projected footprint of the pastel tip. 2) Define the contact area and compute the amount of pigment removal. 3) Derive net bidirectional pigment transfer rates between the pastel and the canvas. 4) Update the attached pigment mixture. 5) Update the pigment layer. 6) Update the paper layer. 7) Carry out the precalculated tip deformation.

7. Apply the in step 3 calculated deformations to the pastel tip.

The following paragraphs will clarify each of these steps in more detail.

Computing the Projected Footprint. One of the most important parts of the simulation is to derive the contact area between the pastel and the canvas. This area is defined as the intersection between the height field of the canvas and the transformed height field of the pastel tip. It also depends on the amount of pressure exerted by the artist; more pressure results in a wider contact area.

First, the texture based model of the pastel tip needs to be converted to the correct transformed height field. Next, the simulation is only executed for that part of the tip closest to the canvas as only the lower part of the transformed tip can deposit pigment. This is done by computing the orthogonal projected footprint of the tip on the canvas, combined with the deployment of a depth test.

To calculate the footprint a combination of a vertex and a fragment shader is used. As input, the individual tip samples are rendered as a set of coplanar vertices. Next, the points are transformed to their actual locations, taking into account the orientation of the pencil and the heights they represent. To each of the resulting fragments a depth value is assigned, indicating their height above the canvas surface. A depth buffer is used to remove tip samples from the pipeline which are located perpendicular above other samples but have higher height values.

Eventually, these calculations result in a footprint of the pastel tip, which is parallel to the canvas surface. Furthermore, it indicates for each participating sample i the distance d_i to the paper sample underneath.

Defining the Contact Area. After calculating the projected footprint, we extract the smallest encountered distance between the tip and the paper surface. Next, we

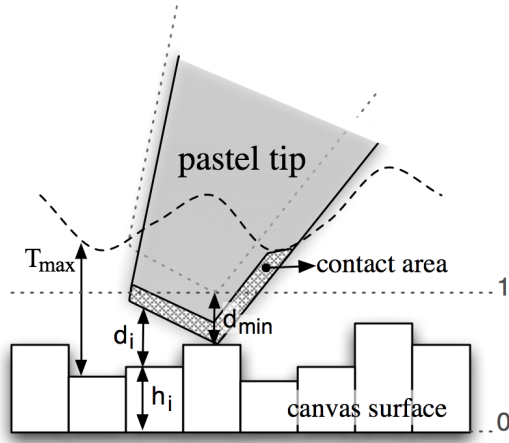


Figure 3 The contact area: Lowering the on the surface positioned pastel tip with the smallest depth d_{min} encountered between the pastel and the paper results in 1 contact point. Tolerating depth values up to T_{max} allow for a larger area of conceptual contacts.

lower all height values from the footprint with this value d_{min} . This results in a contact at exactly one point (see Figure 3).

However, in real life, a higher pressure will result in a larger contact area. This is because a bigger part of the tip gets pressed into the canvas, resulting in a larger intersection between both height fields.

To compensate for this, we introduce a distance tolerance T_{max} , indicating the threshold under which the earlier calculated distances should be in order to belong to the contact area. Relating this tolerance value to the pressure allows for a larger contact area when more pressure is exerted.

Calculating the Head Deformation. Given the contact area, the amount of pressure and the properties of the canvas and pastel, a shader is used to calculate the amount of pigment that will break off the tip.

First, we estimate for each sample in the contact area their degree of participation to the contact. That is, samples that are located close to the paper get a high degree of participation, whereas samples that were added due to the tolerance value receive a lower value. This factor is reduced exponentially depending on the distance between the samples' position and the paper.

$$\tau_i = 1 - (T_{max} - d_i) / T_{max} \quad (1)$$

$$C_i = \exp(-\tau_i \cdot \sigma) \quad (2)$$

Considering τ_i to estimate the participation of sample i to the contact, it is clear that with an exponential drop off only values close to 0 result in larger participation values C_i for a given constant value σ , and this vice versa. A σ value of 5 was selected to achieve satisfying results.

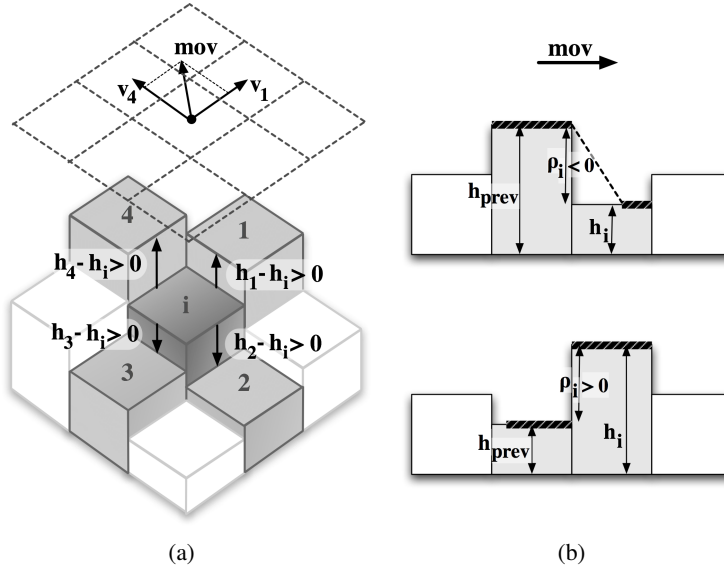


Figure 4 a) The roughness of the paper depends on the differences between the current samples height h_i and the height values of its 4 direct neighbors: h_1, h_2, h_3 and h_4 . Positive differences are added up according to the similarity between their relative location vector v_n and the current drawing direction mov . b) Contact friction: the length of the friction against a paper sample is estimated by the difference in height between the current sample i and the previous sample $prev$.

Next, we take into account the structure of the paper. Rough paper breaks off more pigment from the tip than a smoother paper surface does.

To estimate the roughness of the paper we locally measure the differences between the current samples height h_i and the height values of its 4 direct neighbors: h_1, h_2, h_3 , and h_4 . We only need the contributions of the two neighbors that might be reached following the current drawing direction mov . To achieve this, a simple dot product is used (see Figure 4(a)). For each neighbor n , a positive value for $v_n \cdot mov$ indicates that it is reachable and its magnitude functions as a weight to indicate the importance of its height difference.

$$R_i = \sum_{n=1}^4 \max((v_n \cdot mov), 0) \cdot \max((h_n - h_i), 0) \quad (3)$$

The resulting value R_i indicates for the current paper sample the weighted sum of all the positive height differences with the neighboring cells that might be reached following the current drawing direction. Rough paper corresponds to higher R_i values and larger depositions of pigment.

As the pastel tip moves along the paper surface, it slides over the surface of each encountered paper sample and deposits an small amount of pigment, taking into account the length of this contact. To compute the contribution of this friction

F_i , we applied an effective heuristic. As a reference for the amount of friction, we use the height difference ρ_i between the current paper sample i and the previously visited paper sample $prev$. If the previous sample was lower, the tip will be able to slide over the full current paper sample and more pigment will be deposited. If the previous sample was higher, the tip will skip a small part of that surface and less pigment will be cut off (see Figure 4(b)).

$$\rho_i = h_i - h_{prev} \quad (4)$$

$$F_i = \begin{cases} (1 + \rho_i)^2, & \rho_i \leq 0 \\ 1, & \rho_i > 0 \end{cases} \quad (5)$$

Given the previously calculated factors, the actual pigment removal can be estimated as follows:

$$D_i = C_i \cdot P \cdot (w_1 \cdot R_i + w_2 \cdot F_i) \cdot \frac{s_{paper}}{s_{pastel}} \quad (6)$$

The deformation D_i of the i th sample depends on the participation factor C_i , the pressure P , the roughness of the paper R_i , the amount of friction F_i , the paper strength s_{paper} , and the strength of the pastel pigment s_{pastel} . Each of these factors is translated to the $[0, 1]$ interval, so each factor has equal contribution to the result. The computation of C_i , R_i and F_i is based on the equations 2, 3 and 5. The pressure factor P allows for larger pigment removals when the artist exerts more pressure onto the pastel. The weights w_1 and w_2 are controlled by the user and indicate the response of the simulation to the paper roughness and/or friction properties. Adding the ratio between the paper strength and the pastel strength as a factor, results in higher pigment depositions when using soft pastels on hard paper, and less pigment removal when using hard pastels on relative softer paper.

Computing the Net Color Transfers. Given the amount of pigment removal for each sample of the pastel tip, a fragment shader calculates the net color transfers and stores them in a texture. These values indicate for each sample the net amount of pigment traveling between the tip and the canvas.

In order to calculate this relation between both media we need to resample them to the same resolution. Using a fragment shader we downsample the pastel contact area to the resolution of the canvas, establishing a 1 to 1 mapping of pastel samples to paper samples. The actual transfer rates will thus be determined in paper space. For each sample, the amount of pigment transferred depends on:

- the pigment properties (e.g., color, staining values, ...),
- the amount of earlier deposited pigments on the paper,
- the amount of earlier attached pigments on the tip,
- the maximum amount of pigment deposition possible.
- the maximum allowed amount of pigment attachment.

First, the quantity of pigment broken from the tip is composed of two components. The first component consists of parts of the pigments soiling the tip, whereas the second component is taken from the pastel stick/pencil itself.

Next, the amounts of pigments to be scraped from the pigment layer are computed (based on a fraction of the amounts of pigments stored at the pigment layer, according to the staining properties of each pigment type), after which they remain sticking to the pastel tip.

Finally, after summing up both values for each pigment type, these net values are subjected to a threshold to take into account the amounts that actually can be deposited on the pigment layer or the pastel tip. The quantity of pigment not delivered to the pigment layer is assumed to reside as dust on top of the canvas surface and will be blown off by the artist.

The last steps in our simulation pipeline consist of updating the different media according to these modifications.

Updating the Canvas. By sampling the transfer texture at the matching positions, the entries of the pigment layer can be modified to reflect the calculated bidirectional pigment transfers.

Similar, small deformations to the paper layer can be carried through. The amount of deformation is related to the calculated transfer value, the pressure exerted on the tip, the strength of the paper, and the strength of the pastel tip. The resulting removal of paper causes particular visual effects to appear. That is, deep carves result in relative smaller contacts, thus allowing for smaller pigment depositions onto the canvas. This is because the edges of the carves break off more pigment from the tip whereas the lower parts of the carve seem to remain relatively unchanged. Figure 6 demonstrates the importance of this effect.

Updating the Pastel Tip. Corresponding to the earlier calculated amount of pigment removal from the tip, both the height field and the attached pigment layer are updated. According to the head staining of each pigment, a sufficient amount of pigment is removed from the attached layer, indicating the quantity of fixed pigment that needs to be removed from the height field.

5 Examples

Our pastel simulation is implemented on a Pentium D 2.8 GHz, using C++ and NVidia's Cg. The setup is equipped with a NVidia GeForce 6800 and includes a Wacom tablet interface that provides 5 DOF, enabling users to control the pencil in an intuitive way. All pastel examples depicted in this paper are drawn in real-time by a novice user, adopting a 768×576 simulation grid resolution.

The strokes in Figure 5 demonstrate the effects of different pigment staining values for both the tip and the canvas. The image in the middle was created using a yellow colored pastel, soiled with black pigment in a non-uniform manner.

In Figure 6, the impact of paper deformation is distinctly visible. First, two yellow strokes are drawn with a variable pencil pressure. Next, after clearing the canvas for demonstration purposes, the area is covered with black pencil strokes, revealing the carves in the paper.

The effect of pastel weathering is depicted in Figure 7. The left part of the figure shows the pencil tip shape respectively before and after drawing the stroke

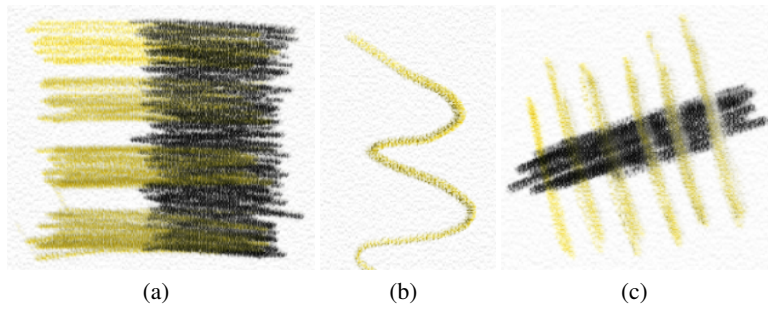


Figure 5 Pigment staining. a) Varying degrees of pigment staining to the tip. Higher values result in longer attachments and more profound soiling of black pigment on the yellow tip. b) A stroke drawn using a soiled tip. Black pigment gets attached to and redeposited from a yellow pastel tip in a non-uniform manner. c) Varying degrees of pigment staining to the canvas. Higher values match with smaller amounts of black pigment scraped from the pigment layer.

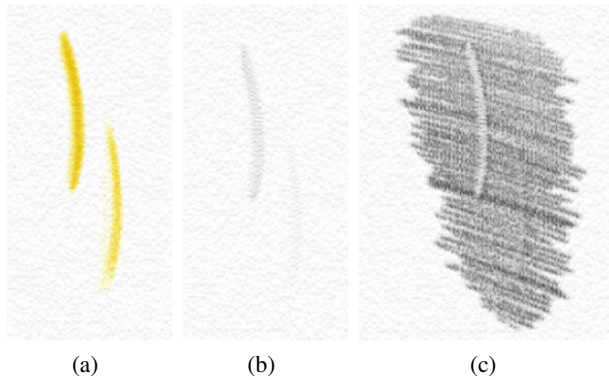


Figure 6 Paper deformations. a) Two yellow pastel strokes drawn with different pressure. b) The corresponding paper deformations (pigments removed for demonstration purposes). c) The result after drawing over the curves with black pastel. Varying degrees of pigment deposition become visible due to the modifications to the paper structure.

shown on the right. During deformation, the stroke's appearance changes accordingly.

Figures 8 and 9 show complete drawings, illustrating the different ways to create color and tonal variations using pastel: (i) *optical blending*, which is achieved by having colors in close proximity (Figure 8), and (ii) *blending*, where the pastel is mixed on the paper (Figure 9).

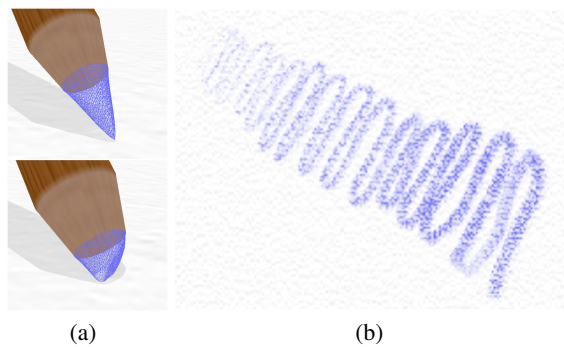


Figure 7 Head deformations (pastel tip visualized in wireframe for demonstration purposes). a) The tip before and after the deformation. b) The shape of a pastel stroke changes as pigment is removed from the tip.

6 Conclusions

In this paper we presented a system for drawing pastel media in real-time. We focused on the simulation of the natural material itself and on its interaction with the drawing surface and the drawing tool. To this end, the system's parameters are directly configured by (i) the artist's personal way of wielding the brush (e.g., pressure, orientation), and (ii) physical features of the drawing material (e.g., concentration of the binder, paper strength, stickiness of the pigment).

While drawing using pastel, a bidirectional transfer of pigment occurs: (i) the deposition of new pigment from the pencil to the paper surface, and (ii) scraping previously deposited pigment from the paper surface. Regarding the latter, part of the scraped pigment will stick to the pencil, soiling its tip and influencing the next set of strokes to be drawn. The dusty remainder, however, does not contribute any further to the drawing and is blown off the paper surface by the artist. Furthermore, both the tip and the paper surface are subject to weathering. As pigment is deposited on the paper surface, a similar volume will be worn from the tip so it becomes blunt, whereas each contact between the pencil and the paper slightly damages the paper surface. That is, due to exerting pressure little grooves are cut in the surface, which restrain a further deposition of pigment.

From a stylistic point of view, similar to traditional drawings our results convey the artists' characteristics (e.g., way of wielding the brush, skillfulness, feeling for the medium). Therefore, we believe our system allows an artist to create realistically looking pastel images without losing his/her personal touch.

Future Work. The emphasis in this paper is on 'dry media'. However, pastel sometimes is combined with other material like watercolor and gouache. In the future we would like to extend our system in order to support those kind of mixed-media paintings.

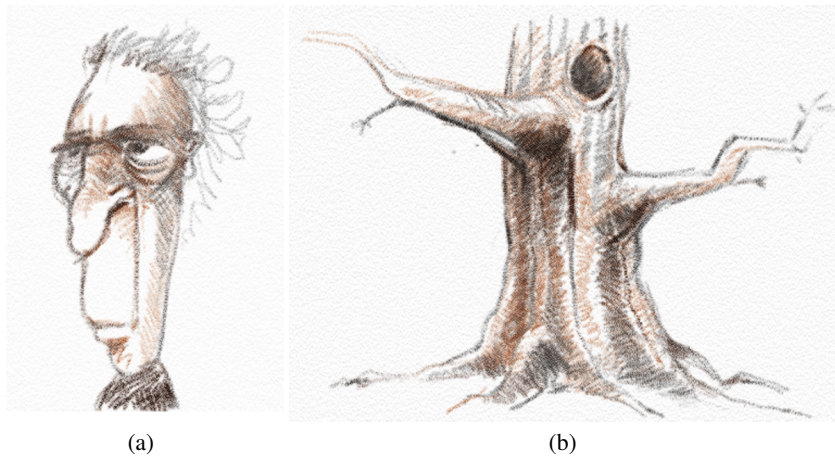


Figure 8 Two pastel drawings illustrating the use of (cross) hatching to create tonal variations.



Figure 9 Two pastel drawings depicting the medium's broad range of vivid colors. Note that all colors originated from only one small set (i.e. 6) of bright pigments by mixing them on the paper surface.

Acknowledgements We gratefully express our gratitude to the European Fund for Regional Development (EFRD), the Flemish Government and the Flemish Interdisciplinary institute for Broadband Technology (IBBT), which are kindly funding part of the research at the Expertise Centre for Digital Media.

Many thanks go also to Marie-Anne Bonnetterre, José Xavier, Bart 'Pokke' Van Bael, and Bjorn Geuns for their artistic contribution.

References

1. Gooch, B., Gooch, A.A.: Non-Photorealistic Rendering. A. K. Peters Ltd., ISBN: 1568811330 (2001)
2. Hebborn, E.: The Art Forger's Handbook, reprint edn. Penguin USA (2004)
3. Kubelka, P., Munk, F.: Ein Beitrag zur Optik der Farbanstriche. In: Z. tech Physik 12 (1931)
4. Mudde: Pastel. Cantecleer, De Bilt (2003)
5. Murakami, K., Tsuruno, R., Genda, E.: Multiple illuminated paper textures for drawing strokes. In: Proceedings of Computer Graphics International (CGI2005), pp. 156–161 (2005)
6. Murakami, K., Tsuruno, R., Genda, E.: Natural-looking strokes for drawing applications. The Visual Computer 22(6), 415–423 (2006)
7. Reynolds, C.: Stylized depiction in computer graphics. World Wide Web, <http://www.red3d.com/cwr/npr/> (2004)
8. Rudolf, D., Mould, D., Neufeld, E.: Simulating wax crayons. In: Proceedings of Pacific Conference on Computer Graphics and Applications (Pacific Graphics 2003), pp. 163–172. IEEE Computer Society, Washington, DC, USA (2003)
9. Rudolf, D., Mould, D., Neufeld, E.: A bidirectional deposition model of wax crayons. Computer Graphics Forum 24(1), 27–40 (2005)
10. Strothotte, T., Schlechtweg, S.: Non-Photorealistic Computer Graphics. Modeling, Rendering, and Animation. Morgan Kaufmann Publishers, ISBN: 1-55860-787-0 (2002)
11. Worley, S.: A cellular texture basis function. In: Proceedings of the 23rd annual conference on Computer graphics and interactive techniques, pp. 291–294. ACM Press, NY, USA (1996)



William Van Haevre is a PhD student at Hasselt University (UHasselt) in Diepenbeek, Belgium. At this university, he earlier obtained a MS in computer science in 2001. His current research interests include computer graphics and animation, physically-based modeling and animation of natural phenomena, video-based animation of plants and simulating highly stylized drawing techniques. During the summer of 2007, he will defend his PhD in computer science at the Expertise Centre for Digital Media (EDM) (a research institute of Hasselt University), on his work concerning the topological realism in the modeling and animation of environment sensitive plant models.



dr. Tom Van Laerhoven is a senior researcher in computer science at Hasselt University (UHasselt) in Diepenbeek, Belgium. He obtained a MS in computer science in 2000 at UHasselt. In 2006, he finished his PhD entitled “An Extensible Simulation Framework Supporting Physically-based Interactive Painting” at the Expertise Centre for Digital Media (EDM), a research institute of Hasselt University. His research activities are concerned with computer animation, physically-based modeling and animation, non-photorealistic rendering and parallel and distributed algorithms.



Prof. dr. Fabian Di Fiore is a senior researcher in computer science at Hasselt University (UHasselt) in Diepenbeek, Belgium. He obtained a MS in computer science in 1997 at the University of Leuven. In 2004, he finished his PhD entitled “A 2.5D Modelling and Animation Framework Supporting Computer Assisted Traditional Animation” at the Expertise Centre for Digital Media (EDM), a research institute of Hasselt University. His research activities are concerned with computer animation, non-photorealistic rendering and highly stylized drawn animation.



Prof. dr. Frank Van Reeth is Professor of computer science at Hasselt University (UHasselt) in Diepenbeek, Belgium. He is deputy managing director of the Expertise Centre for Digital Media (EDM) at UHasselt. He obtained a MS in computer science in 1987 at the Free University of Brussels and a PhD in computer science at UHasselt in 1993. His research interests include computer graphics, computer animation, networked virtual environments, human computer interaction and multimedia technology. He published over 100 scientific papers in the above domains. He is a member of ACM, the Computer Graphics Society (CGS), Eurographics and IEEE.