

Object-Space Painterly Rendering for WebGL

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Figure 1: *The Stanford bunny rendered with 3 layers of brush strokes.*

Abstract

We produce painterly images of 3D models by covering them in a particle system of brush strokes. Strokes move along with the original object, producing smooth animations. Strokes are rendered in multiple layers; higher layers show detail and appear in areas of high specular value. Strokes orient and curve themselves along edges and towards centers of light. We have avoided the use of the painter’s algorithm or 2D post-processing.

Keywords: Painterly Rendering, Non-Photorealistic Rendering, Particle Systems, Painting, GPU Processing

1 Introduction

Non-photorealistic rendering (NPR) aims to bridge the gap between the creativity and expressivity of traditional art and the interactive and automated world of digital computer graphics. Various NPR techniques have applications in games, films, architecture, and scientific visualization. Painterly rendering is a subset of NPR that tries to create images that have a painted appearance, as if the image was created from a sequence of brush strokes on a canvas.

Painterly rendering research typically focuses on brush stroke properties, methods of user interaction, rendering techniques, and other

methods of approximating natural artwork.

Many past painterly algorithms [Hertzmann 1998], [Lu et al. 2010] have first generated a “real” image using other methods, then attempted to draw it as a painting. This brings with it the computational cost of fully rendering the scene twice, as well as a “shower door” visual effect where 2D strokes do not move perfectly in sync with 3D geometry.

Like others [Meier 1996], we instead keep a scene of brush stroke particles. There is no “real” rendering but the paint, and strokes store their own color and calculate their own light. Strokes are transformed along with the original geometry, allowing them to be controlled by a physics engine (in our case, `cannon.js`). In video games, there is also the potential to change brush stroke properties according to an object’s state - for example, a damaged character glowing red. It would also be possible for painted objects to appear along-side those rendered in other styles.

1.1 Related Work

The use of particle systems to create painted images was explored in “Painterly Rendering for Animation” [Meier 1996]. Paint particles are distributed onto 3D objects and undergo the same transformation. During the rendering phase, a reference picture rendering is first created using traditional methods. Then every particle is sorted by depth, and particles are drawn back-to-front. Particles take on the color of the reference picture, or a solid color may be used per-particle and the reference picture ignored. The color is applied to a stroke texture (called the “brush image”), which is finally applied to the screen at the particle’s (projected) location.

[Lu et al. 2010] uses a hybrid approach - strokes are attached to the screen in 2D but (in the case of a 3D animated scene) follow the motion vectors of objects. There is still a slight grainy look as strokes are stochastically killed and reborn when passing object boundaries. Their approach is also suitable to video camera footage. Like us, they use multiple stroke layers and a variety of stroke parameters (in their approach, these parameters are applied to the whole image

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Project Repository: <https://github.com/ScottTodd/PainterlyRendering>

at once rather than to a particular object.)

In [Hertzmann 1998], 2D input images are painted over by layers of spline brush strokes. Strokes are placed along areas of high gradient on a source image blurred proportionally to the current brush size. In this manner, progressive emphasis is placed on regions of high visual interest. An intuitive collection of parameters is chosen such that a user may easily select between a spectrum of visual styles. Parameter sets are presented for “Impressionist”, “Expressionist”, “Colorist Wash”, and “Pointillist” styles.

[Kalnins et al. 2002] explores interactive techniques that allow artists to create non-photorealistic renderings of 3D models. Artists are given control over brush styles, paper textures, basecoats, background styles, and the position and styling of each stroke. Their system uses information supplied from one or more viewpoints to render the models at any new viewpoint while preserving the desired aesthetic.

2 Painterly Rendering System

2.1 Algorithm Overview

We represent brush strokes as particles within particle systems. (The particles will be referred to as “strokes”.) Each object in the scene is represented as any number of layers; each layer has its own particle system.

Our system creates stroke meshes out of three.js geometries. Other inputs will include layer, color, and lighting information. The system outputs an image to a WebGL canvas.

```
Algorithm 1: Painterly Rendering Overview
[Section 2.2] At load time : foreach object do
  foreach layer do
    | Create a “stroke mesh” particle system
  end
end
[Section 2.3] At run time : foreach frame do
  Render a depth image
  foreach object do
    foreach layer from bottom to top do
      foreach stroke do
        Compute stroke properties in the vertex shader
        1. [Section 2.3.1] Compute zQuality
           (closeness to desired depth) and discard
           strokes with negative zQuality
        2. [Section 2.3.2] Compute diffuse and
           specular lighting and discard strokes with
           specular less than the minimum
        3. [Sections 2.3.3 - 2.3.6] Compute the
           “drawing gradient” at the stroke’s position,
           which provides the stroke’s orientation and
           curvature
        [Section 2.3.6] In the fragment shader, render an
        oriented, curved, colored version of the stroke
        texture according to the above parameters
      end
    end
  end
end
```

2.2 Stroke Mesh Creation

2.2.1 Stroke Selection

Rather than storing models directly as stroke systems, our system loads three.js JSON object files. These are transformed into stroke systems in the client using a method similar to that of [Meier 1996]. The total number of particles to be placed on the mesh is a parameter. Then for each face on the mesh, the number of particles on that face is in proportion to its area; in other words, it is that face’s fraction of the total area, times the total number of particles. Random Barycentric coordinates are selected, and position and normal values are interpolated between the face’s vertices.

Strokes on the same object are drawn in the same order every time, so if strokes are generated one face at a time in this way, rendered images will show an undesirable ordering of particles. So, strokes are shuffled once during the loading phase.

2.2.2 Color Selection

To color strokes, the user may select random hue, saturation, and luminance ranges for colors to be chosen from. This produces aesthetically pleasing representations of what are essentially “solid” colored objects.

2.3 Rendering

2.3.1 Rendering Overview

Both the original triangle mesh and stroke meshes are needed for rendering. We render in two passes. First, we render the original geometry into a (floating point) depth texture. Then, we may render objects in any order, but render lower stroke layers before higher layers. Some higher-layer strokes will decide to discard themselves. (As WebGL does not yet support geometry shaders, discarding a stroke is done by shrinking it to 0 size and moving it offscreen.)

We also render object borders by fattening the original and drawing only triangles which face away from the camera. This is visually pleasing, but not necessary for our method.



Figure 2: The Stanford bunny rendered into a depth buffer texture. Note that areas close to the screen are lighter than areas further from the screen.



Figure 3: On the left, all $zQuality$ values are set to 1. Backfacing strokes render, causing black marks. It is unclear which portions are in front. On the right, $zQuality$ is used, so only strokes that should be showing are drawn and strokes fade in smoothly along the edges.

2.3.2 $zQuality$

Good results may be achieved by sorting particles by depth, but at the cost of performance. Blending particles is also unsuccessful because the number of overlapping particles is unpredictable. So, within each layer, particles are always drawn in the same order and always draw on top of each other. This leads to occlusion issues when a layer overlaps itself (see Figure 3).

This depth texture is passed as a uniform into the vertex shader for paint strokes. Each stroke measures its depth compared to the expected depth, and fades out as the difference increases. We scale opacity by an amount $zQuality$ defined as:

$$zQuality = 1.0 - \frac{(modelViewPosition.z - depthTextureZ)}{zEpsilon}$$

Where $zEpsilon$ is a parameter such that greater values cause strokes to fade in over a greater distance. A simple on/off threshold ($zEpsilon \ll 1$) would work, but strokes just showing up coming around the edge of an object would suddenly “pop” into existence.

We could have discarded fragments rather than whole strokes, but decided that the visible clipping of strokes that would result was undesirable.

There is still another problem for strokes just at the edge of an object, which may on some frames barely extend beyond its depth buffer, leading to negative $zQuality$ and a discarded stroke; and on other frames fit perfectly; meaning that these strokes would flicker on and off. A slight fattening of the original mesh ensures that all of its strokes fit within its borders. We fattened the original mesh by pushing each vertex a small distance along its normal.

2.3.3 Lighting

Each stroke is shaded solidly, using the light calculated at its center. We use the Phong equations. Light is calculated per stroke (in the vertex shader), rather than per-fragment. The total diffuse and specular lighting are calculated separately (see section 2.3.9).

2.3.4 Use of Gradient

For each stroke, we calculate a “drawing gradient” property which strokes will be drawn perpendicular to. We would like strokes to satisfy the following attributes: they should follow the contours of objects and not extend far beyond the edges; and they should

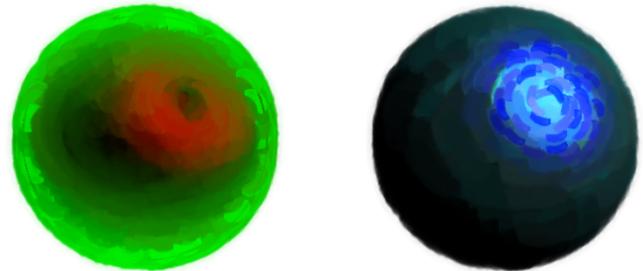


Figure 4: Left: Strokes are green where $edgePart$ is high, red where $lightPart$ is high, and transparent otherwise. Right: Lit version. Note how strokes circle around the center of light, and also align along the sphere’s edges.

circle around centers of light. To satisfy these, we calculate the “net gradient” of the image based on both position and lighting attributes. These two parts are called the “edge gradient”, which points away from edges towards the center, and the “light gradient”, which points towards centers of high light intensity (see Figures 4-5).

We calculate their contributions with this formula:

$$\begin{aligned} edgePart &= \|edgeGradient\| \\ lightPart &= \min(lightFactor \times \|lightGradient\|, \\ &\quad (1 - edgePart)^2) \\ drawingGradient &= edgePart \times norm(edgeGradient) + \\ &\quad lightPart \times norm(lightGradient) \end{aligned}$$

Near the edges, only the edge gradient will factor in. It is more important that strokes align along the silhouette edges than that they circle the light. $lightFactor$ is a parameter measuring how important the light gradient is, but $lightPart$ can never exceed $(1 - edgePart)^2$. This quantity is squared to strictly reduce it; without squaring, $lightPart$ would still occasionally overwhelm $edgePart$, making strokes leak past object edges.

2.3.5 Edge gradient

The edge gradient is simply the x and y of the projected normal. Strokes whose normals point straight at the viewer have no edge

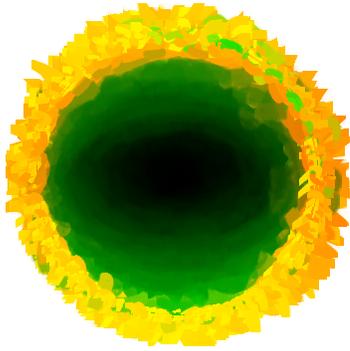


Figure 5: To create this image, *lightPart* was defined as $lightFactor \times ||lightGradient||$. Specular light is just coming in on the edge, driving the gradient wild.

gradient, meaning that there is no desire to orient them along the edges of the object, as they are likely in the middle. Strokes whose normals point straight to the side have an edge gradient of length 1, meaning that they are on the very edge of the object and there is a strong desire to orient them along it.

2.3.6 Light gradient

The light gradient is estimated without the expense of creating a reference image, meaning a Sobel filter is not used. Instead, we consider the changes in lighting as a viewer looks across the surface of an object. To do this, we calculate the direction from the camera to each stroke. This direction is then moved a small amount to the camera's right or up (for the gradient's x and y components, respectively). A second ray is then fired from the camera and assumed to hit the same object. We approximate the local surface as a sphere and use a ray/sphere collision solver to find the new intersection. (The sphere's radius is the mesh's curvature at that position. We currently hard-code this, but it may be calculated at load-time [Gatzke and Grimm 2006].) The lighting intensity is then calculated with the new position and normal there to find the difference in light. So, the lighting equation is run 3 times per stroke.

2.3.7 Orientation and Curvature

Stroke orientation is the gradient rotated 90 degrees. The amount of curvature is determined by multiplying the gradient length by the parameter *curveFactor*; strokes always curve along the gradient. Since strokes are point sprites, orientation and curvature are done using image transformations in the fragment shader.

First, the fragment coordinate is rotated around the stroke center by the orientation. Then it is distorted according to curvature (see Figure 6). Fragments with $x = 0.5$ will remain unaffected, while fragments near $x = 0$ or $x = 1$ will sag down in a parabola whose height scales with the curvature amount.

$$yDistort = curveAmount \times (x - 0.5)^2$$

The stroke texture sampling is then taken at $(x, y - yDistort)$. The stroke texture controls opacity, not color. The fragment shader's output is the stroke's shaded color, with an opacity value or the stroke texture sampling.

2.3.8 Layering

As in [Hertzmann 1998], [Meier 1996], and [Lu et al. 2010], we use multiple layers of brush strokes for each object. Usually, the base layers will contain fewer, larger brush strokes. The base layers



Figure 6: From left to right: no orientation or curvature, orientation with no curvature, orientation and exaggerated curvature (2.0).

capture rough, un-detailed areas and completely cover the object's silhouette, while the top layers show fine details and may leave gaps between each other. We found that three layers of strokes were sufficient for the scenes that we tested. Layers have completely separate properties, making for interesting visual effects; for example, a base layer may be unsaturated and have a rougher stroke texture.

2.3.9 Specular Fade In

We support having higher-layer strokes fade in to only areas of high specular light. If the specular lighting contribution at a stroke does not exceed a (user-specified) minimum value, it is discarded. Strokes with low specular will be partly transparent, allowing for a smooth transition. This allows us to approximate the visual interest sampling in [Hertzmann 1998] and [Lu et al. 2010]; however, our method does not draw small strokes along object borders. (If such was really desired, it could be done by considering the magnitude of edge gradient.)

2.4 Parameters List

The following properties may be specified per-layer:

1. Number of strokes
2. Stroke size
3. Stroke texture
4. Curve factor
5. Color range (hue, sat, lum)
6. Specular amount and power
7. Specular fade-in range

These may be specified by calling our API or through a user interface we created for this purpose.

3 Results

Our system renders 60 frames per second with 250,000 strokes at an 1000 by 500 pixel resolution on an ATI Radeon HD 5770 graphics card in Google Chrome. Users were able to edit parameters using our user interface to create their own designs.

The variety of parameters allows a wide range of styles (Figures 7-10). Artistic skill plays a large role in producing a quality image. Even without a texture, interesting images are created through layering and random variations in stroke color.

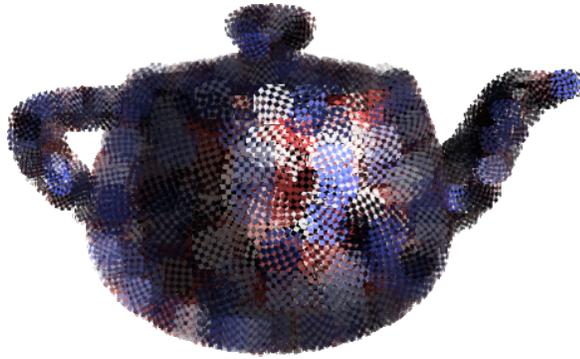


Figure 7: American teapot. All strokes are checkerboards. A sparse blue layer is rendered on top of a red layer. Varying luminance causes some strokes to be black or white.

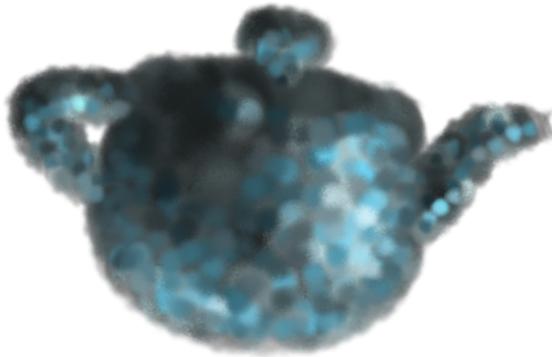


Figure 8: The Utah teapot rendered using three layers of brush strokes. The topmost layer uses a specular fade-in.

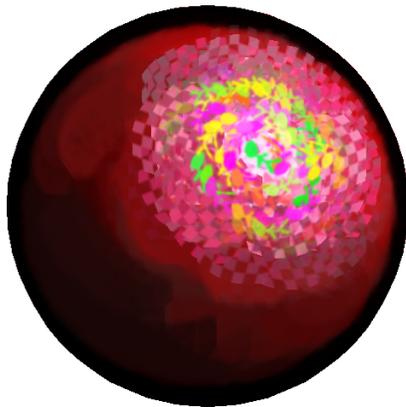


Figure 9: Different layers may have different properties. Large red unsaturated strokes lead to medium pink grids leading to rainbow stick figures.

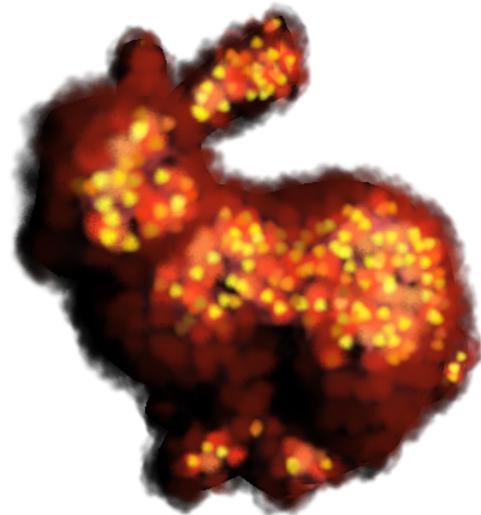


Figure 10: The Stanford bunny demonstrating some of our parameters. The base layer contains large, dark, desaturated brush strokes. The top layer disappears below a minimum specular and fades in as specular increases.

4 Limitations and Future Work

Our method achieves smooth zooming by scaling strokes down when they are farther away. Thus, objects in the distance may be drawn with many small strokes rather than with a few well-placed strokes.

The primary efficiency issue with our method is that every stroke is stored as a particle with position, normal, and coloring information. For large objects with many small strokes this would have a great data cost. Most strokes are discarded in most frames, whether because they are occluded or do not reach their minimum specular value. One improvement might be to perform stroke generation in a geometry shader and only store the mesh as data. (Unfortunately, WebGL does not yet support geometry shaders.)

Our method does not cull strokes at object boundaries, instead curving them inwards. This would not work well for objects to be rendered with sharp corners (e.g. a dagger). However, per-fragment culling could be easily added, at the cost of unappealingly slicing strokes in two.

We are also exploring the use of textures for color selection. If a model provides a set of UV coordinates at each vertex on a face, we can interpolate those UV coordinates and perform a lookup into a texture. We can then use that color for the brush stroke instead of a random color. To preserve details, we could strategically place upper-layer strokes at areas of high gradient in the texture, similar to what others [Hertzmann 1998], [Lu et al. 2010] have done to painterly images as a whole.

There remains the possibility of controlling stroke parameters in real time based on how a game plays out. Values passed to the vertex shader as uniforms are animatable - this includes texture, size, curvature, and specular parameters. It may also be desired to efficiently animate what are currently specified as shader (per-stroke) attributes - for example, stroke colors on a character may increase in saturation when the character is selected. This could be done by adding uniform factors or offsets for stroke attributes.

5 Conclusions

We have presented an interactive painterly rendering system that runs in a web browser using 3D models as inputs. Our system considers brush stroke depth, lighting, and “drawing gradient” while rendering. Our system uses layers, color variation, stroke textures, and other parameters to allow for customization.

Non-photorealistic rendering techniques such as painterly rendering allow for great artistic freedom within computer graphics. As in photorealistic rendering, care must be taken to accurately represent objects within the scene, which can be challenging when working with a constrained set of visual components.

Acknowledgments

We developed our system using three.js.

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