Generating Textures on Arbitrary Surfaces Using Reaction-Diffusion

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Abstract

This paper describes a biologically motivated method of texture synthesis called *reaction-diffusion* and demonstrates how these textures can be generated in a manner that directly matches the geometry of a given surface. Reaction-diffusion is a process in which two or more chemicals diffuse at unequal rates over a surface and react with one another to form stable patterns such as spots and stripes. Biologists and mathematicians have explored the patterns made by several reaction-diffusion systems. We extend the range of textures that have previously been generated by using a cascade of multiple reaction-diffusion systems in which one system lays down an initial pattern and then one or more later systems refine the pattern. Examples of patterns generated by such a cascade process include the clusters of spots on leopards known as rosettes and the web-like patterns found on giraffes. In addition, this paper introduces a method by which reaction-diffusion textures are created to match the geometry of an arbitrary polyhedral surface. This is accomplished by creating a mesh over a given surface and then simulating the reaction-diffusion process directly on this mesh. This avoids the often difficult task of assigning texture coordinates to a complex surface. A mesh is generated by evenly distributing points over the model using relaxation and then determining which points are adjacent by constructing their Voronoi regions. Textures are rendered directly from the mesh by using a weighted sum of mesh values to compute surface color at a given position. Such textures can also be used as bump maps.

CR Categories and Subject Descriptors: I.3.3 [Computer Graphics]: Picture/Image Generation; I.3.5 [Computer Graphics]: Three-Dimensional Graphics and Realism - Color, shading, shadowing and texture; J.3 [Life and Medical Sciences]: Biology.

Additional Keywords and Phrases: Reaction-diffusion, biological models, texture mapping.

Introduction

Texture mapping was introduced in [Catmull 74] as a method of adding to the visual richness of a computer generated image without adding geometry. There are three fundamental issues that must be addressed to render textures. First, a texture must be acquired. Possibilities include creating a texture procedurally, painting a texture, or digitally scanning a texture from a photograph. Next, we need to define a mapping from the texture space to the space of the model to be textured. Defining this mapping should not require a great deal of a user's time. This mapping should not noticeably distort the texture. Finally, we require a method of sampling the texture during rendering so that the final image contains no artifacts due to aliasing or resulting from the underlying texture representation [Heckbert 89]. These three issues are often interrelated, and this is true of the techniques in this paper.

This paper explores a procedural method for texture synthesis and also introduces a new method for fitting a texture to a surface. Either of these techniques can be used separately, but the examples given here shows the strength of using them together to produce natural textures on complex models. After a discussion of previous texturing methods, the majority of the paper is divided into two parts, one for each of these topics.

The first part of this paper describes a chemical mechanism for pattern formation know as *reaction-diffusion*. This mechanism, first described in [Turing 52], shows how two or more chemicals that diffuse across a surface and react with one another can form stable patterns. A number of researchers have shown how simple patterns of spots and stripes can be created by reaction-diffusion systems [Bard 81; Murray 81; Meinhardt 82]. We begin by introducing the basics of how a reaction-diffusion system can form simple patterns. We then introduce new results that show how more complex patterns can be generated by having an initial pattern set down by one chemical system and further refined by later chemical systems. This widens the range of patterns that can be generated by reaction-diffusion to include such patterns as the rosettes found on leopards and the multiple-width stripes found on some fish and snakes. These patterns could be generated on a square grid and then mapped onto an object's surface using traditional techniques, but there are advantages to synthesizing the pattern directly on the surface to be textured in a manner that will be described next.

The second part of this paper presents a method of generating a mesh over the surface of a polyhedral model that can be used for texture synthesis. The approach uses relaxation to evenly distribute points across the model's surface and then divides the surface into cells centered at these points. We can simulate reaction-diffusion systems directly on this mesh to create textures. Because there is no mapping from texture space to the object, there is no need to assign texture radiate from these special cells. One way to create an initiator cell is to slightly raise or lower the substrate value at that cell. Another way is to mark the cell as frozen and set the value of one of the chemicals to be higher or lower than at other cells. The pseudo-zebra in Figure 6 was created in this manner. Its stripes were initiated by choosing several cells on the head and one cell on each of the hooves, marking these cells as frozen and setting the initial value of chemical g_1 at these cells to be slightly higher than at other cells.

Varying Parameters Across a Surface

On many animals the size of the spots or stripes varies across the coat. For example, the stripes on a zebra are more broad on the hind quarters than the stripes on the neck and legs. Bard has suggested that, after the striped pattern is set, the rate of tissue growth may vary at different locations on the embryo [Bard 77]. This effect can be approximated by varying the diffusion rates of the chemicals across the computation mesh. The pseudo-zebra of Figure 6 has wider stripes near the hind quarters than elsewhere on the model. This was accomplished by allowing the chemicals to diffuse more rapidly at the places where wider stripes were desired.

Part Two: Mesh Generation and Rendering

This section describes how to generate a mesh over a polyhedral model that can be used for texture synthesis and that will lend itself to high-quality image generation. The strength of this technique is that no explicit mapping from texture space to an object's surface is required. There is no texture distortion. There is no need for a user to manually assign texture coordinates to the vertices of polygons. Portions of this section will describe how such a mesh can be used to simulate a reaction-diffusion system for an arbitrary polyhedral model. This mesh will serve as a replacement to the regular square grids used to generate Figures 2 and 3. We will create textures by simulating a reaction-diffusion system directly on the mesh. It is likely that these meshes can also be used for other forms of texture synthesis. Such a mesh can be used for texture generation wherever a texture creation method only requires the passing of information between neighboring texture elements (mesh cells).

There are a wide variety of sources for polyhedral models in computer graphics. Models generated by special-effects houses are often digitized by hand from a scale model. Models taken from CAD might be created by conversion from constructive solid geometry to a polygonal boundary representation. Some models are generated procedurally, such as fractals used to create mountain ranges and trees. Often these methods will give us few guarantees about the shapes of the polygons, the density of vertices across the surface or the range of sizes of the polygons. Sometimes such models will contain very skinny polygons or vertices where dozens of polygons meet. For these reasons it is unwise to use the original polygons as the mesh to be used for creating textures. Instead, a new mesh needs to be generated that closely matches the original model but that has properties that make it suitable for texture synthesis. This mesh-generation method must be robust in order to handle the wide variety of polyhedral models used in computer graphics.

Mesh generation is a common problem in finite-element analysis, and a wide variety of methods have been proposed to create meshes [Ho-Le 88]. Automatic mesh generation is a difficult problem in general, but the requirements of texture synthesis will serve to simplify the problem. We only require that the model be divided up into relatively evenly-spaced regions. The mesh-generation technique described below divides a polyhedral surface into cells that abut one another and fully tile the polyhedral model. The actual description of a cell consists of a position in $\mathbf{R}^3$, a list of adjacent cells and a list of scalar values that tell how much diffusion occurs between this cell and each of its neighbors. No explicit geometric representation of the

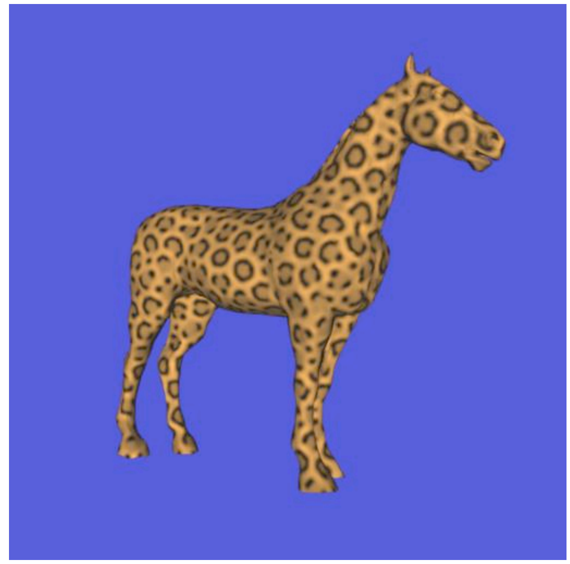

Figure 4: Leopard-Horse

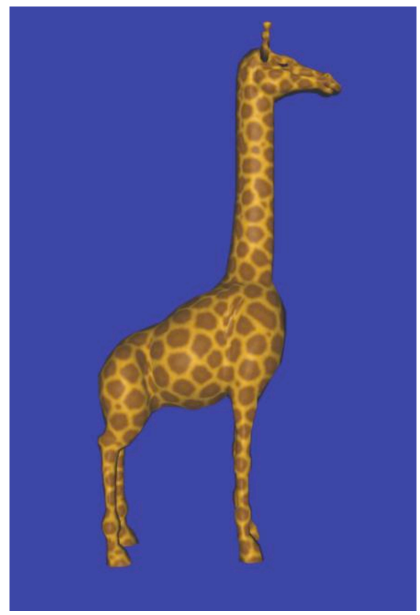

Figure 5: Giraffe

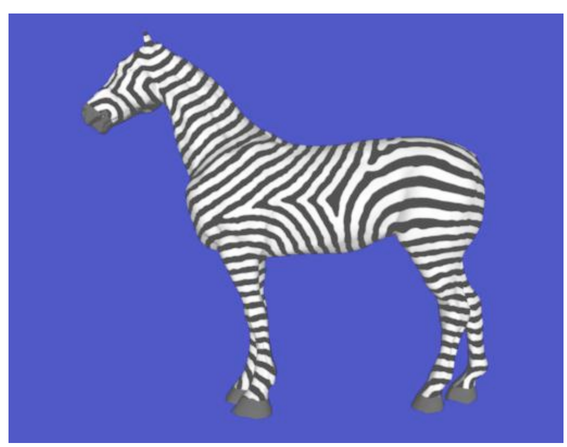

Figure 6: Pseudo-Zebra