Flow and Changes in Appearance

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Abstract

An important, largely unexplored area of computer image generation is the simulation of weathering and its effects on appearance. Weathering results from the interaction of the environment with the materials in the world. The flow of water is one of the most pervasive and important natural forces involved in the weathering of materials, producing a distinctive set of patterns of washes and stains. This paper presents an intuitive phenomenological model for the flow of water over surfaces that is capable of generating such changes in appearance.

We model the flow as a particle system, each particle representing a "drop" of water. The motion of the water particles is controlled by parameters such as gravity, friction, wind, roughness, and constraints that force the particles to maintain contact with the surface. The chemical interaction of the water with the surface materials is governed by a set of coupled differential equations describing both the rate of absorption of water by the surface and the rate of solubility and sedimentation of deposits on the surface. To illustrate the power of this simple model, we show examples of flows over complex geometries made from different materials; the resulting patterns are striking and very difficult to achieve using traditional texturing techniques.

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Additional Key Words and Phrases: weathering, material models, physically-inspired texturing, particle systems, light reflection models.

1 Introduction

Over time, the natural environment acts upon materials and changes their appearance. These processes and changes are termed *weathering*. Through weathering, objects become tarnished, bleached, stained, eroded, and otherwise modified. Weathering is unavoidable and therefore must be simulated to make realistic pictures of natural environments.

For many years, computer graphics researchers and practitioners have been grappling with the problem of creating surfaces that have a worn appearance. In the production of Pixar's recent computer-generated film *Toy Story*, for example, weathering effects such as scuffs and dirt were added to the surfaces by painting textures and compositing them within a programmable shader [6]. However, this process is very time consuming. Current tools for texturing geometric models made from many surfaces are primitive; for example, it is very difficult to match textures across surface boundaries or account properly for area distortions caused by the parameterization. More fundamentally, the texture mapping approach does not take into account the structure or properties of a given material or the processes in the surrounding environment that account for weathering. Our long range goal is to simulate the effect of the environment on complex material surfaces so that their appearance may be controlled semi-automatically.

The focus of this paper is the modeling of changes in appearance caused by the flow of water over complex surfaces. Figure 1 contains several photographs we have collected showing the weathering of various buildings. Inspection of these photographs reveals that many of the complex patterns on the surfaces are due to the flow of water. Water may wash dirt from some areas and clean them; in other areas dirt and other materials are deposited, creating stains. The patterns produced by this process are visually rich and very difficult to model with current texturing techniques.

Exactly how water travels over surfaces is very complicated and is dependent on a large number of variables. Unfortunately, the workings of complex flows are still not fully understood based on first principles [1]. However, for the purposes of this study, we are concerned with the patterns created by the flow of water on surfaces, not the detailed appearance of the flow itself. We therefore present a phenomenological model, based on particle systems and rate equations governing the absorption of water by the surface and the sedimentation of deposits. This model is simple and robust, and it is capable of generating a wide range of flow effects.

1.1 Related Work

Relevant previous work can be conveniently divided into two major categories: techniques for simulating fluid flow and particle systems. In this section, we discuss our approach in light of these categories.

Flow models. Kass and Miller presented an approach for animating water using a set of partial differential equations [8]. They used a wetness map to simulate the wetting and drying of sand as water passes over it. Miller and Pearce described a model for animating viscous fluids by simulating the forces of particles interacting with one another [12]. The focus of both of these works was on the realistic appearance of the flow itself, both in terms of its motion and rendering. In addition, Musgrave et al. proposed a simple, heuristic erosion model that simulates hydraulic and thermal erosion processes on fractal terrains [14].

Particle systems. Particle systems represent an effective approach to modeling objects whose behavior over time cannot be well-represented in terms of the surface of the objects [17, 18]. In such a system, a collection of particles evolves over time. The

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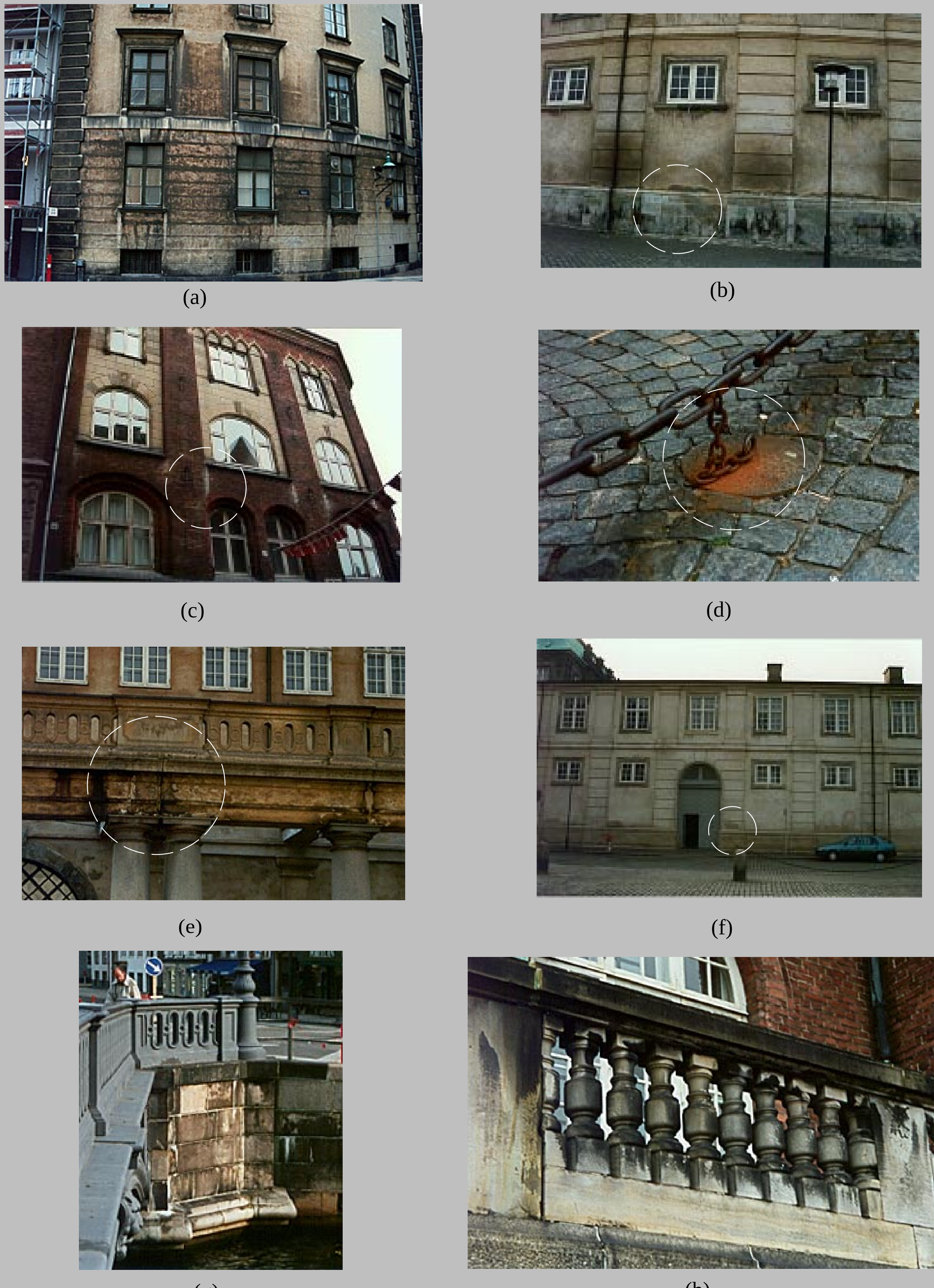


Figure 1. A collection of representative flow effects.

evolution is determined by applying certain rules to the particles. Particle motion may follow either deterministic or stochastic laws of motion. Particle systems have been used to model trees, grass, fog, waterfalls, and fire [5, 16, 23].

In a related work, Small described a parallel approach to the problem of modeling watercolor by predicting the actions of pigment and water when applied to paper fibers [19]. This model was cast as a complex cellular automata on the Connection Machine II. Small's model produces nice results, but it is limited to two dimensions and requires excessive processing power.

The specific technical contribution of this paper is to combine particle systems with processes similar to those used to model water colors. This allows us to simulate the effects of material transport on complex surfaces.

1.2 Overview

The remainder of this paper is structured as follows. We first introduce the basic mechanisms of flow and staining and give examples of typical effects that inspired our work. We then describe our flow model in detail, both the dynamics of particles and the coupled differential equations controlling absorption and sedimentation. Finally, we illustrate the model with examples of flows over complex geometries: a building facade, two statues, and a portion of a Gothic cathedral.

2 Background

Figure 1 features photographs of real scenes that show many effects of the flow of water over surfaces. In this paper, we will demonstrate that a number of these effects can be captured with a simple underlying model. In this section we describe the motivation behind the development of our model with a discussion of the mechanisms of flow and staining including a review of the major factors involved. We then discuss a series of specific representative effects that are associated with this process.

2.1 Exposure and Runoff

The basic factors affecting the rate of flow over a surface are the quantities of incident water, the height, inclination and geometry of the surface, and the absorption of water by the material comprising the surface [1, 4].

One of the major features of the pattern of flows on a building is the arrangement of water sources. From these sources, water flows downward under the influence of gravity. This is often termed *primary flow*. This depends on which parts of the structure receive the most incident water and the effect of geometry on directing the flow. Typically the flow separates into streams, and, in a way similar to rivers, produces patterns that often become self-reinforcing. Figure 1a shows a typical example of flows on a wall of moderate exposure. In particular, the window sills and lintels above the windows serve to concentrate the flow on both sides of the windows.

The absorption of water by the surface is controlled by the *absorptivity*, or rate of water uptake, and the *absorption*, or capacity to absorb water. *Runoff* occurs when the surface is fully saturated (i.e. has no more capacity to absorb water) or non-absorbent (i.e. has a low absorptivity). Figure 2 shows the relationship between incident rain, runoff, and absorption for several materials [2]. Curve A represents a spongy material with high absorptivity and absorption. This material has the capacity to absorb all the incident water over time, hence there is no runoff. Curve B describes a moderately absorbent concrete with high absorptivity but a limited absorption capacity. Initially, from t_0 to t_2, all incident water is absorbed and there is no runoff. However, from t_2 to t_3, because of

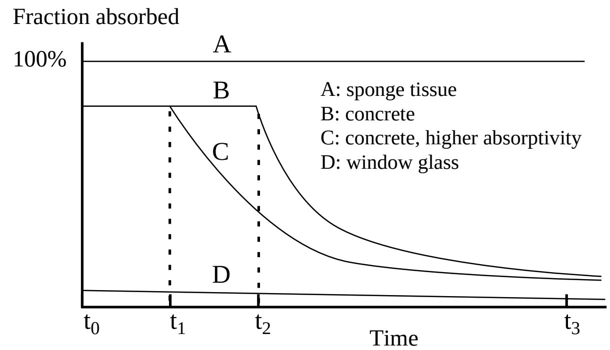


Figure 2: Simplified diagram showing absorption over time for several materials assuming a constant rain.

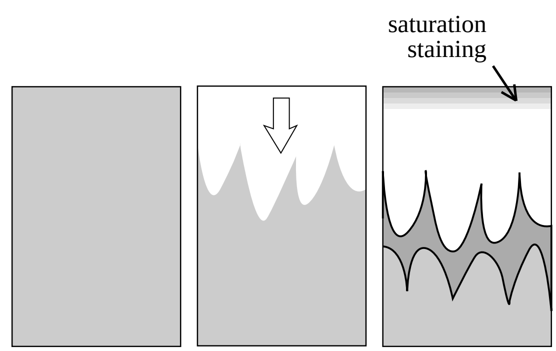
saturation, the amount absorbed is less than the incident amount; hence, some rain is absorbed but an increasing quantity runs off. In Curve C, which gives the behavior of concrete with a higher absorptivity, runoff starts sooner, because the material becomes saturated more quickly. Finally in Curve D, which describes a very non-absorbent material such as glass, the amount of water that is absorbed is very small and drops off slowly during the time span; thus there is significant runoff.

The exposed parts of a structure become saturated first, so the flow starts there and proceeds onto dryer areas below. These lower surfaces absorb a proportion of the water until they too have a rate of incidence that exceeds the rate of absorption.

Splashback is a phenomenon that occurs where a wall meets the ground. Here, water hits the ground adjacent to the building and causes dirt from the ground to be propelled up and deposited a short distance up the wall. This effect also occurs when water hits horizontal ledges higher up on a building. Figure 1b shows an excellent example of splashback at the base of a building.

2.2 Staining

The washing and staining of surfaces are strongly influenced by external, directional sources of dirt. These sources include a variety of airborne pollutants, such as exhaust from traffic or smoke emissions from industrial plants, loose material on the ground carried against the base of the building by splashback, or dirt of a biological source ranging from bird droppings to plant growth.



(a) Even deposit of dirt (b) Water from above picks up some dirt... (c) ...redepositing it at the limit of flow

Figure 3: The basic mechanisms of staining.

In Figure 1h, the pattern of dirt on the spindles in the balustrade is due to a directional dirt source. The effect of an external source can also be observed in Figure 1a. The right side of the building curves away from the street, which leads to a reduction in the exposure to dirt caused by street traffic.

Without the effects of rainfall, dirt would be distributed fairly evenly over vertical surfaces, with higher concentrations on horizontal regions such as window sills. Although large quantities of dirt are disfiguring (as is the case with buildings completely blackened by soot), generally an even distribution of dirt due to exposure is not considered staining. However, a different picture emerges when water flows over a surface. Dirt is picked up by water movement and redeposited elsewhere, so that its distribution becomes uneven. The areas that are exposed to a rapid flow of water may be washed clean, whereas those where the dirt is redeposited have a greater accumulation. This basic mechanism is illustrated in Figure 3.

An interesting effect occurs at the locus of points on the surface where the runoff stops; this interface is critical with respect to staining, since this is where any dirt picked up by the runoff water is redeposited [10]. A very similar stain occurs when water evaporates, leaving behind any soluble material. Another interesting effect occurs when a non-absorbent surface is adjacent to a porous surface. In this case, the staining is limited to the porous material. In Figure 1g, the top portion of the bridge is made of a non-absorbent metal, which causes a large portion of the incident water to run onto the porous stone work below, causing significant staining.

Another important effect in staining is *differential flow*, which occurs when water running over one material dissolves small quantities of the material and deposits them as stains elsewhere. A common example, known as the *spilt-milk* effect, can be readily observed in places where runoff from concrete leads to white streaking on brickwork below. Other examples include green stains generated by runoff from copper [3] or rust stains from other corroded metals such as iron. If there are several materials present, even more complex patterns of stains may occur depending on the relative solubilities of the different materials. Figures 1c and 1d depict examples of differential flow. In Figure 1c the circled region shows the spilt-milk effect caused by the deposits from a limestone window sill. In Figure 1d the circled region shows an example where rust from an iron chain has been washed onto the street below.

In areas that are exposed to water for long periods of time, *saturation staining* often occurs. Different materials have a different color response to saturation; most porous materials become darker due to a decrease in the average scattering angle caused by the interaction of the water and the substrate. Figure 1f illustrates saturation staining. Here, water collects on the ridge at the base of the building.

3 Flow Model

In this section, we describe a model that qualitatively captures many of the flow effects described in the previous section. The model has three basic inputs: surface geometry to create structures, materials for the structures and loose deposits, and the environment. Our flow simulator is based on particle systems and rate equations. Particles are used to model water "droplets" both on the surface and in the air. The environment description specifies the initial distribution of water droplets. Equations of motion describe the movement of each water particle over the surface accounting for gravity, friction, contact forces, and the influence of obstacles. The quantity of water in a particle decreases through absorption into the base material of the surface or evaporation. Water droplets may dissolve material, carry it to a different location, and subsequently deposit it there. This model is simple conceptually, is easy to implement, and only requires modest computation.

Surface geometry is represented as a collection of parametric patches. The current system supports two types of patches: polygons and cubic spline patches. The geometric information is augmented with topological information that describes adjacency relationships between all the patches; this is essential because the flow must be continuous across a patch boundary. Each parametric surface also has a set of two-dimensional texture coordinates which is used to index a set of texture maps attached to each surface. For example, the amount of water absorbed by the surface is stored in a *saturation map.*

In addition to water, the system also models other materials. Each patch represents a surface of a solid object made from a base material, which is coated with a mixture of loose deposits. The concentration of each loose deposit is stored in a texture map attached to the surface. Each type of material has an associated set of rendering properties, e.g. diffuse and specular colors, shininess, and a set of physical properties, e.g. roughness, absorptivity, and other rate constants. These properties are summarized in Table 1.

Material Properties		
	Properties	Notation
Material	Diffuse color	C_d
	Specular color	C_s
	Shininess	s
	Roughness	r
	Absorption	a
	Absorptivity	k_a
Deposits	Diffuse color	C_d
	Adhesion rate constant	k_S
	Solubility rate constant	k_D

Table 1: Attributes of the two major classes of materials: base materials and loose deposits. Rate constants (properties beginning with k) are used in the differential equations controlling absorption of water and sedimentation of loose deposits (see Table 3).

3.1 Water Particle Model

In our model water is represented as a collection of water particles. The attributes of each water particle are shown in Table 2; they include the mass or volume of the particle, as well as positional attributes. Particle systems have been used widely in computer graphics and the techniques we use for modeling their motion are well described in the literature [20, 22].

Water Particle Properties	
Attribute	Notation
Mass	m
Position	x
Velocity	v
Soluble material i	S_i

Table 2: Particle attributes.

Water particles are created on the geometric model according to a distribution function for incident rain. This function depends on exposure to the prevailing rain direction. These distribution functions will be discussed in more detail in Section 3.4. The flow of water particles along the surface depends on a set of forces: gravity, friction, self-repulsion, and diffusion. Gravity and friction cause the particles to flow downward; self-repulsion prevents the particles from clumping and causes the motion to be more fluid-like (see Figure 4). Normally the flow of particles is constrained to lie on the surface; this is done by projecting the resulting force vector onto the

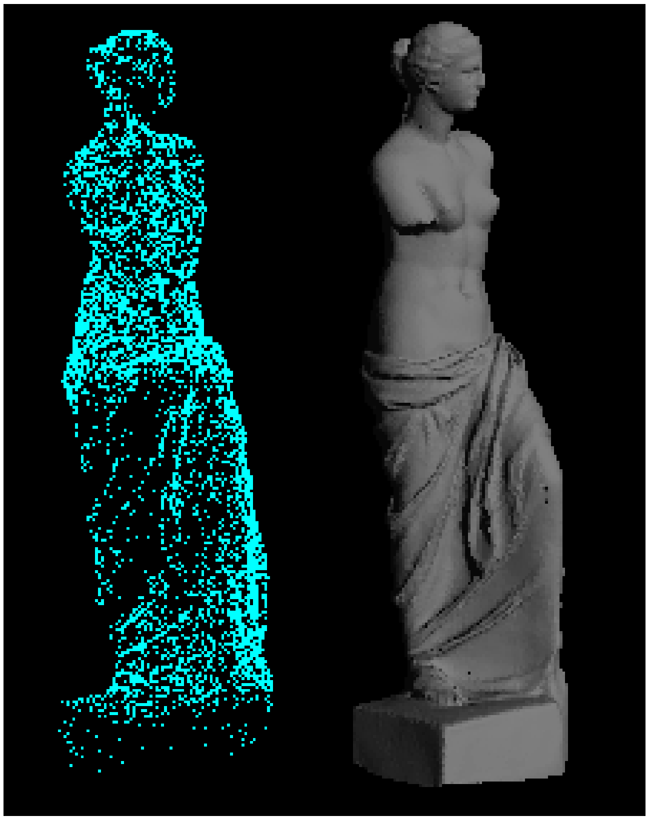


Figure 4: Particle simulation on a complex model.

tangent plane of the surface, as described in Turk [20]. Obstacles are detected by comparing the surface normal at subsequent time steps. If the surface normal changes abruptly, a probability distribution function determines whether the particle should continue on its present course, or ricochet away from the obstacle.

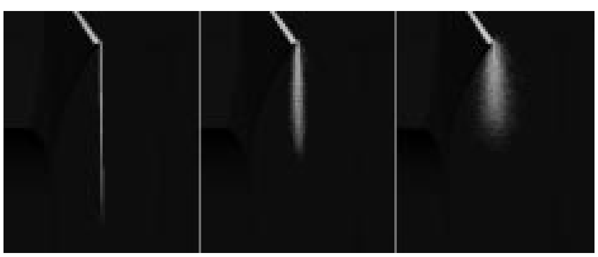


Figure 5: The effects on the flow due to surface roughness. The three figures are generated with different surface roughnesses: the surface on the left is smoothest; the surface on the right is roughest.

In order to create more interesting flows on surfaces that are geometrically smooth, we have experimented with two simple rough surface models. In the first model, a scalar roughness controls a diffusion process. To simulate diffusion, each particle is subjected to a random force in the tangent plane to the surface; the magnitude of the displacement force is proportional to the roughness parameter. Figure 5 shows the effect of roughness on the flow. As can be seen, increasing the roughness causes the particles to disperse, whereas decreasing the roughness causes the flow to be streaky. In the second model, a displacement map is added to a surface. The displacement map is used to perturb the surface normal which in turn defines a perturbed tangent plane. When a displacement map is present, the resulting force is first projected onto the true tangent plane and then reprojected onto the perturbed tangent plane. This simple technique causes the particles to conform to the displacement map — flowing more slowly across a bumpy surface and hence collecting in cavities and cracks, and streaming along cracks and valleys.

To model the effects of secondary flow, particles are allowed to fall off a surface. A particle leaves the surface if the angle between its velocity vector and the surface tangent exceeds a prespecified critical angle. When a particle loses contact with the surface, it falls vertically under the influence of gravity until it hits another surface. Since computing such intersections can be computationally intensive, we pre-compute a table of positions where particles will land when they fall off the surface. This is an important feature, as our models consist of large numbers of patches.

Together, these steps form a model capable of reproducing a sufficiently wide variety of effects to generate interesting weathered appearances. Complex flow patterns arise naturally by constraining particles to remain on the surface, thereby forcing the particles to conform to the geometry. Collisions naturally divert particles around obstacles and allow for non-local interactions between different parts of the model. Roughness and displacement maps change the look of flows on different surfaces. A snapshot of particles flowing over a complex surface is shown in Figure 4.

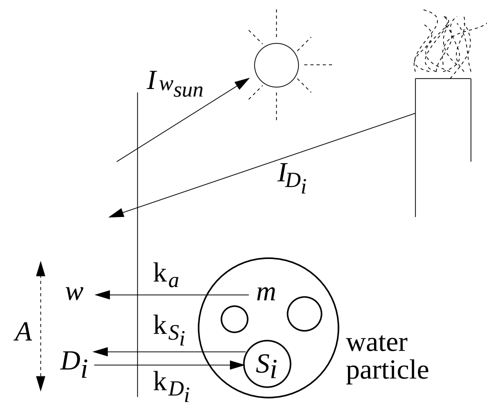


Figure 6: Absorption and deposition model.

3.2 Absorption Model

The absorption of water by a surface depends largely on the properties of void space, or pores, in the material. However, for practical purposes the following model is often adopted [2]: Three parameters control the absorption: *absorption*, *absorptivity*, and *saturation*. Absorption is the maximum amount of water that the surface may hold, whereas absorptivity is the rate that the surface absorbs water. Saturation is the ratio of the actual water absorbed to the capacity of the surface. The amount of water absorbed depends on the absorptivity and the duration of exposure, but it is limited by the absorption. This effect can be modeled by adjusting the absorptivity as a function of the saturation.

The absorption process is shown diagrammatically in Figure 6, and the equations that govern the process are contained in Table 3. As a water particle moves across a porous surface, its mass will decrease due to absorption and evaporation. At each time step, after the position of the particle is updated, its mass is updated by numerically intergrating a differential equation controlling absorption and evaporation. When the mass of the particle falls below some threshold, it "dies" and is removed from the simulation.

Absorption and Deposition Process
Absorption
$\frac{\partial m}{\partial t} = -k_a \frac{a-w}{a} \frac{A}{m}$
$\frac{\partial w}{\partial t} = k_a \frac{a-w}{a} \frac{m}{A} - I_{w_{sun}}$
Sedimentation
$\frac{\partial S_i}{\partial t} = -k_{S_i} S_i + k_{D_i} D_i \frac{m}{A}$
$\frac{\partial D_i}{\partial t} = k_{S_i} S_i \frac{A}{m} - k_{D_i} D_i + I_{D_i}$

Table 3: Sedimentation equations. The top two equations control the absorption of water by the surface; the bottom two equations control the sedimentation of loose deposits. In this last set of equations, the subscript i is used to signify different types of deposits. S_i is the concentration of dissolved material in a water particle, and D_i is the concentration of material deposited on the surface. All other parameters and functions are described in Tables 1 and 2.

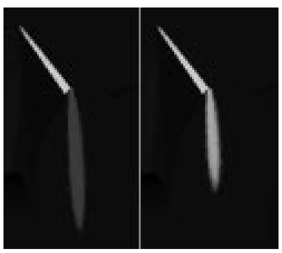


Figure 7: The effects on the flow due to absorption of a porous surface. The two figures show the amount of absorbed water on two surfaces with different absorptions. Because the surface on the left has a lower absorption than the one on the right, it becomes saturated sooner and the water streak is longer. In contrast, the surface on the left absorbs more water limiting the length of the streak. Since more water is inside the streak on the right, the streak is brighter.

Figure 7 illustrates the flow pattern from a pipe across a surface with two different absorptions. To make these images, the quantity of water absorbed at each point by the surface is stored in a saturation map. This saturation map may be used by the rendering system to modulate the appearance of the surface. Unlike this figure, a saturation stain makes the surface appear darker; this point will be discussed in Section 3.5.

3.3 Deposition Model

The last main category of surface attributes controls transport and deposition of various substances such as dirt. In our model, these sedimentation characteristics are captured by two parameters: *solubility*, describing the rate at which water picks up surface deposits, and *adhesion*, specifying the rate of redeposition from water particles on to the surface. These parameters may vary for different materials.

The sedimentation process is shown diagrammatically in Figure 6, and the equations governing the process are shown in Table 3. These coupled differential equations depend on the relative concentrations of the materials in the water particle and on the surface. In the case of a water particle, the concentration is defined to be material per unit mass; in the case of the surface, the concentration is the material per unit area. Note that as a water particle's mass decreases due to evaporation, the concentration of dissolved materials decreases. Thus, the rate of deposition naturally increases during evaporation, causing the dissolved material to be deposited on the underlying surface.

The relative solubility and adhesion of deposits on a surface play a major role in the generation of stains. When water dissolves material from a surface, it has the effect of washing the surface. When water deposits material, it has the effect of staining the surface. The combination of these two effects, when coupled with the flow, can generate complex stain patterns. Even more complex patterns arise if multiple materials with different solubilities are present. More examples of this will be shown in the results.

3.4 Environment Model

Environment attributes	
Attribute	Notation
Rain	$I_{w_{rain}}$
Sunlight	$I_{w_{sun}}$
Deposits	I_{D_i}

Table 4: Environment

The external factors affecting the flow are shown in Table 4. In this section we describe the models we used to generate the images in this paper. Although it should be emphasized that it is very easy to add more complex environmental models to the system.

As described in Section 3.1, the rate and direction of incident rain seeds the particle flow process. We model this by creating rain sources that emit rain drops. In our model, the direction of rain is controlled by the direction of wind. This in turn is given by randomly perturbing the prevailing wind direction. These drops are traced until they intersect the model and are deposited in an exposure map. For efficiency reasons we precompute these exposure maps. During the flow simulation the exposure determines the probability that a water particle will be created at different points on the surface; however, once a particle is created, water sources have no effect on the particle's mass.

The rate of evaporation is very sensitive to the orientation of the surface and whether it is shadowed. This effect may be modeled by computing the total solar irradiance, both due to the sky and the sun itself. In some of the experiments performed in this paper, the evaporation rate is set to be constant.

Finally, the initial distribution of deposits of various types may also be controlled with directional sources, or prestored in a texture map.

3.5 Rendering

To create final renderings, we use simple methods to approximate the diffuse color of the loose deposits and to account for wet surfaces and saturation stains. The color of the deposit layer is computed simply by summing the color of each deposit, weighted by the concentration of that deposit from the appropriate texture map. An alpha value is computed using a similar technique, and this is used to composite the deposit color over the base material. The color of a wet surface is modified to make it look darker. To approximate this effect, we simply modulate the diffuse reflectivity depending upon the saturation of the surface.

4 Results

In this section we show results for four complex models: a building facade, two statues, and a section of a cathedral.

Figure 8: Building facade. Rendering without flow patterns (left). Rendering with flow patterns (right).

4.1 Building Model

Figure 8 shows side-by-side renderings of the building, without (on the left) and with (on the right) the flow effects. Figure 9 shows the changes in appearance due to the flows in more detail. The building was modeled using AutoCAD and consists of approximately 450 polygons. All the flow effects in this series were created in approximately three hours on a Silicon Graphics Reality Engine2 with a 250 Mhz R4400 processor.

In the center section of the building alongside the main window, there are several examples of primary flows that continue until the water reaches the stone work comprising the base of the building. The flow has the effect of washing dirt and soot from the brick and depositing it on the lower parts of the building. Note the difference between the patterns generated by the flows on the yellow brick and grey stone below. This is caused by the greater roughness of the brick surface relative to the smoother stone. On the stone at the base of the building, there are subtle splashback effects making the lower part even dirtier. Notice the underside of the vertical panels that curve outward to the left of the yellow brick section: here there is evidence of saturation staining. There is also staining due to partial flows on the sign below the lamp, in this case simulating a rust stain where the lamp meets the building. Similar staining and accumulation of a patina [3] are shown on the copper rain pipe on the left side of the building. Finally, on the sides of the upper window there is a pattern due to the differential flow of the copper patina.

To compute these images, the simulation results are stored in standard texture maps, and these are input into the rendering system. Each surface has nine texture maps, thus the final rendering uses over 4,000 texture maps (although a fair number of these are very small). In our system, we combine the texture maps using a shading language similar to the one used in RenderMan. In these images, displacement maps are used to vary the height of the surface of bricks and stones; ray tracing is used so that the displacement maps self-shadow the surface, which adds to the realism of the pictures.

4.2 Venus de Milo

Figure 10 shows the development of washing and staining patterns due to flows over a statue of *Venus de Milo*, a classic work of art. The model was created from a Cyberware scan and consists of approximately 260,000 small, evenly sized triangles. This data was then used to create 63 bicubic patches, which are input to the flow simulation system. All the flow effects in this sequence were created in a session of approximately twenty minutes in length.

The left image depicts the original, white marble statue prior to the flow simulation. It is pure white, with no imperfections, and is rendered with only diffuse reflection and a single light source.

The right image shows the results of applying a uniform coating of reddish brown dirt across the statue, followed by a flow simulation to wash the surface. There are noticeable streaks in the dirt patterns due to the flow, and a randomness due to the individual nature of each particle. Dirt accumulates in various parts of the statue where the surface is protected from the path of the flow, such as under the left arm. The dirt texture conforms to the folds in the fab-

Figure 9: Closeups of flow patterns on the building facade.

ric below. For example, the upper surfaces of the convex parts of the folds are clean; the lower surfaces are dirty. The pattern is more uniform on the base of the statue and areas closest to the ground, since less water reached that part of the statue. It is not possible to achieve these effects with simple accessibility [11]. The image was rendered using a diffuse model for the marble, and the dirt layer was composited using the same technique as for the building.

4.3 Gargoyle

Figure 11 shows a scanned model of a gargoyle before and after the application of a simple flow pattern. The model was created from a Cyberware scan and consists of approximately 310,000 triangles. This data was then used to create 30 bicubic patches, which were input to the flow simulation system. The reflection function of the metallic surface was modified to make the surface appear as if it were covered by a thin layer of soot that was partially washed away.

4.4 Cathedral

Figure 12 shows a portion of a Gothic cathedral, which was simulated in our system. The cathedral and its statues and gargoyles were modeled using approximately 100,000 polygons which then had displacement maps applied to them, leading to a geometric complexity of over 6,000,000 polygons. The gutters and drainage system on the cathedral were carefully designed to be similar to those on actual cathedrals: water flows down the upper roof to a gutter below the railing which directs the water down the main columns, and down along the top of the flying buttresses [9]. Water exits the system below the statues of the saints. The gutter above the middle section of the facade was blocked, so that the gutter backed up and the particles spilled over the front of the building. As a result, there was much less flow beneath the statue of the saint on the left than the statue on the right. All flow simulations were performed using the displacement maps, so that the flow conformed to the actual displaced geometry; this is evident in the cracks between the stones.

5 Summary and Discussion

We have described a system for simulating the flow of water over complex surfaces. The flow conforms to the geometry of the shapes, and the water interacts with the surface materials. Specifically, the system is able to simulate the absorption of water by the material and the transport of deposits by dissolving and carrying surface material, and later redepositing it. As a result, a wide range of flow effects may be simulated, yielding complex patterns showing washing and staining.

The system is simple, robust, and practical. By using particle systems a wide range of phenomena are easily programmed. We believe the system can be extended to include additional factors, such as windblown dust and biological growth. Also, by embedding the flow model in an interactive system, the user can control the flows to produce the desired images, which is required if a physical model is to be used for artistic purposes. Finally, the methods we use to describe textures on complex surfaces are fairly general; they could be

Figure 10: Simulated flows on *Venus de Milo*. Rendering without flow patterns (left). Rendering with flow patterns (right).

used as a basis for the creation and design of other complex patterns on these surfaces.

Water flows are a major cause of the weathering of outdoor structures and objects and must be simulated to create convincing pictures of such environments. The key to modeling weathering is to simulate the effects of the environment on the materials. Although our pictures have many effects new to computer graphics, it takes only a few minutes studying and comparing the real to the virtual examples to realize that there is still much research to be done. This is a challenging new direction for computer graphics.

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Figure 11: Simulated flows on a gargoyle. Rendering without flow patterns (top). Rendering with flow patterns (bottom).

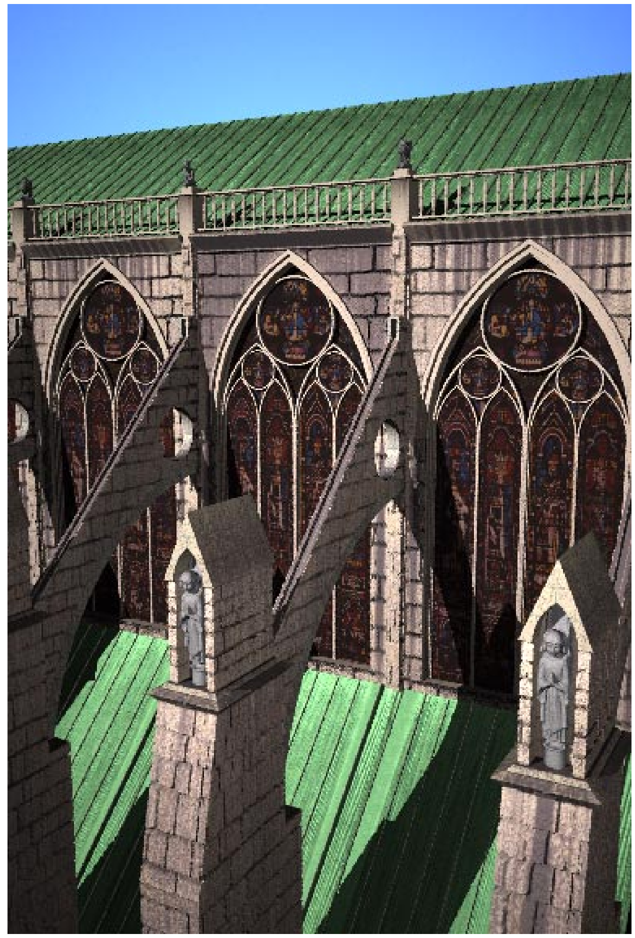

Figure 12: Simulated flows on a Gothic cathedral.

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