Flow and Changes in Appearance

Julie Dorsey
Lab for Computer Science
Department of Architecture
MIT

Hans Køhling Pedersen
Computer Science Department
Stanford University

Pat Hanrahan
Computer Science Department
Stanford University

Abstract

An important, largely unexplored area of computer image generation is the effect of weathering on appearance. Weathering results from the interaction of the environment with the materials in the world. Of the natural forces involved in the weathering of materials, the flow of water plays a major role—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 represent the flow with a particle system and differential equations. These coupled differential equations control both the rate of absorption of water by the surface, and the rate of sedimentation of deposits on the surface. The motion of the water particles is governed by forces due to gravity, friction, wind, roughness and constraints that maintain contact with the surface. The surface material model contains parameters such as absorption, solubility and adhesion that govern the interaction of water and deposits with the surface.

The system runs in both batch and interactive modes, allowing the user to direct the outcome of the simulation. A wide range of effects can be simulated by simply adjusting parameters affecting the flow until the desired effects are achieved. To illustrate the power of this simple model, we show two examples of flows over complex geometries and the resulting changes in appearance: a building facade modeled as polygons, and a statue made from bicubic patches. The resulting patterns are striking, and very difficult to achieve using traditional texturing techniques.

1 Introduction

Over time, the natural environment acts upon materials and changes their appearance. The processes associated with these changes are termed *weathering*. Through weathering, objects become tarnished, bleached, stained, dented, and otherwise modified. Weathering in some form 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, dirt, etc. were added to the surfaces by creating textures with a paint system and combining them with a programmable shader[8]. However, this process is very time consuming and tedious. 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 due to 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 the weathering. The long range goal of this work 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 the flow of water over surfaces and changes of appearance caused by that flow. Plate 1 shows several photographs we have collected showing the weathering of various buildings. By inspecting these photographs, it is apparent that many of the complex patterns on the surface is due to the flow of water. Water washes dirt and other surface deposits from some areas, and stains other areas with the material that has been picked up. 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 complex and dependent on a large number of variables. Unfortunately, the theory of complex flows is still not fully understood based on first principles [1]. Fortunately, for the purposes of this study, we are concerned with the patterns created by the flow of water on surfaces, and 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 is able to generate a wide range of flow effects.

In addition, we briefly describe an interactive tool for controlling this flow model. The tool allows the user to guide the simulation to achieve the desired effects. This is done by interactively controlling the initial conditions, by localizing the simulation to areas of interest, and by sequencing flows to mimic the effect of long exposure to multiple flows.

1.1 Related Work

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

Modeling. Procedural textures [6, 22, 20, 28, 33, 26] represent a wide variety of automatic tools for synthesizing interesting, natural-looking patterns. In the computer graphics literature, there are a few examples of approaches that relate to the modeling of weathering effects. Becket and Badler [3] modeled surface imperfections through texture specification and generation techniques, which are based on fractal subdivision and simple distribution models. These techniques are helpful for simulating the appearance of some surface imperfections. Hsu and Wong [11] introduced functions for simulating dust accumulation that attempt to mimic the dust adherence process. Miller [15] proposed a set of algorithms for local and global accessibility shading, which give the effect of a tarnished surface that has been polished.

While some of the above approaches address the problem of creating surfaces with weathered appearances, none attempt to model the global interaction between environment and the materials making up the surface.

Rendering. There are also several relevant rendering approaches. The most popular approach for modeling the realistic appearance of materials is to construct a surface as a series of layers. For example, RenderMan is often used in this way; the famous bowling pin model is a classic example of this approach [29]. Given the thickness of a dust layer, Blinn modeled the appearance of dusty surfaces with a subsurface shader [4]. The modeling of the reflection and transmission of light through layered surfaces is also relevant [10, 34]. In addition, Gondek et al. and Westin et al. have developed systems for determining the BRDF from surfaces with internal structure [9, 30].

Flow models. Kass and Miller present an approach for animating water using a set of partial differential equations [13]. A wetness map was used to simulate the wetting and drying of sand as the water passes over it. Miller and Pearce present a model for animating viscous fluids by simulating the forces of particles interacting with one another [16]. The focus of both of these works is on the realistic appearance of the flow itself, both in terms of its motion and rendering. In addition, Musgrave et al. describe a simple, heuristic erosion model that simulates hydraulic and thermal erosion processes on fractal terrains [18].

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 [23, 24]. In such a system, a collection of particles evolves over time. The 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 [7, 21, 35]. 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 [27]. This model was cast as a complex cellular automata on the Connection Machine II. This model produces nice results, but it is limited to two-dimensions and requires excessive processing power.

The specific technical contributions of this work are to merge 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

In this paper, we consider the flow of water over surfaces as one example of the simulation of weathering effects. The remainder of this paper is structured as follows. Section 2 introduces the basic mechanisms of flow and staining and gives examples of typical effects that inspired our work. It is followed by a description of the basic flow model and its interaction with surfaces. In Section 4 we describe a set of interactive controls that allow a user to interactively control the development and placement of flow patterns on surfaces. Results are presented in Section 5. The final section presents a discussion of the approach and some directions for future work.

2 Background

Plate 1 features a collection of photographs of real scenes that show many effects that are due to 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 motivate the development of our model with a discussion of the mechanisms of flow and staining followed by a review of the major factors involved. We then discuss a series of specific representative effects that are associated with this process.

2.1 Mechanisms of flow and staining

In this paper, the term *flow* refers to the many ways in which water travels over the surface of materials [2]. The first way is the downward flow of water under the effect of gravity. This is often termed *primary flow*. The second—*secondary flow*—is the splashing back of water against a surface, either from rainfall striking the ground or from water striking a horizontal surface.

The basic factors affecting the rate of flow over a surface are the quantities of incident water, the height and inclination of the surface, and its absorptivity [1, 5](see Figure 1). The absorptivity of the material regulates the proportion of water absorbed by the material and the proportion that continues to flow over the surface, which is termed *runoff*. Figure 2 shows the relationship between incident rain, runoff, and absorption for several materials [2].

Typically the flow separates into streams, determined by fine variations in the absorption and geometry of the surface. In a similar way to streams and rivers, these patterns often become self-reinforcing, especially on soluble materials [36]. From the point of view of staining, it is the random pattern of broken streams with a slow rate of flow that cause the worst disfigurement. A flowing continuous film will cause much more even washing.

In order for staining to occur, there must be *dirt* on the surface. [1] Dirt includes fine atmo-

[1] While water flow alone might cause a change in appearance as a result of erosion, this is not normally a problem for most surfaces. Materials that are soft enough to be weathered by running water would have serious shortcomings in terms of basic durability. In this paper, we do not consider erosion.

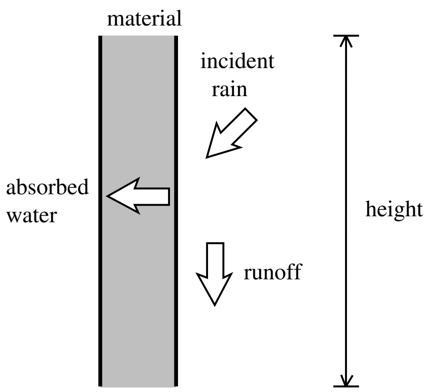

Figure 1: Factors affecting the flow of water over surfaces.

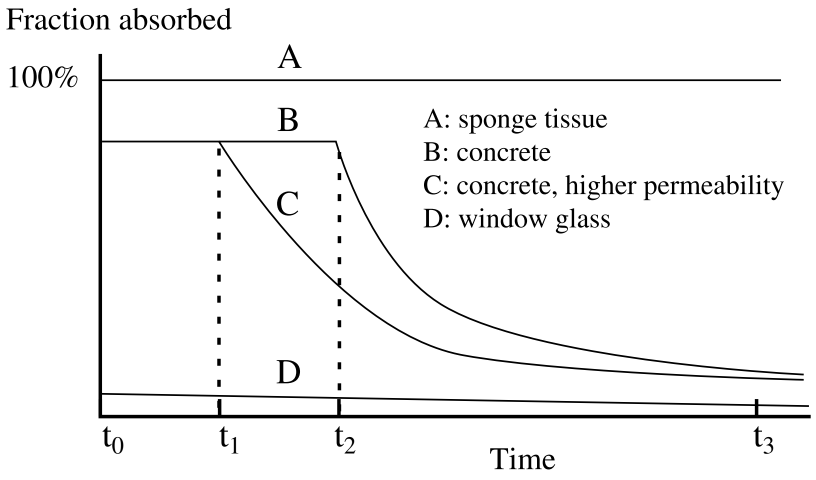

Figure 2: Simplified diagram showing the relationship between incident rain, runoff, and absorption for several materials. Curve A (very absorbent sponge tissue): from t_0 to t_3, the amount of water absorbed equals the amount incident on the surface, so there is no runoff. Curve B (moderately absorbent concrete): from t_0 to t_2, the water absorbed equals the amount incident.. All rain is absorbed and there is no runoff. From t_2 to t_3, the amount absorbed is less than the incident amount, so some rain is absorbed but an increasing quantity runs off because the capacity of the material to absorb water has been exceeded. In Curve C (concrete with a higher permeability): runoff starts at t_1, reflecting a higher absorptivity. Curve D (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.

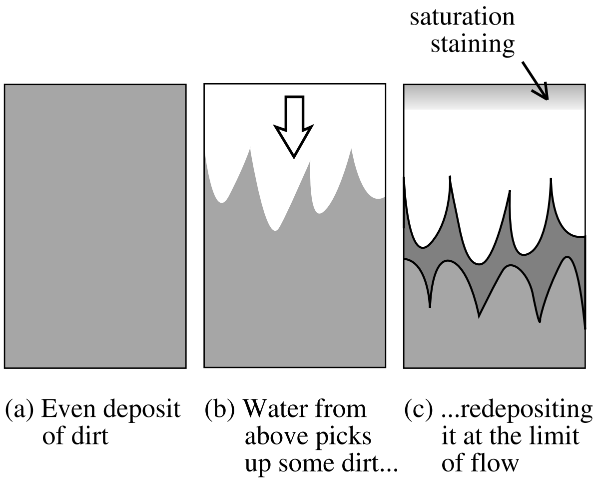

Figure 3: The basic mechanisms of staining.

spheric pollution, such as dust, grit, and soot, 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 growths.

Without the effects of rainfall, dirt would be distributed fairly evenly over vertical surfaces, with higher concentrations on surfaces closer to horizontal surfaces such as window sills. Even though its quantity may be disfiguring (as is the case with buildings completely blackened by soot), it is unlikely that the distribution due to exposure would ever naturally be so uneven as to constitute staining. However, with the effects of water on a surface, a different picture emerges. Dirt is picked up by water movement and redeposited elsewhere, so that its distribution becomes uneven. The areas that are most exposed to runoff and flow of water are washed cleaner than they might otherwise have been, whereas those where the dirt is redeposited have a greater accumulation. This basic mechanism is illustrated in Figure 3.

Factors that affect the washing and redeposition process are the rate of flow of water over the surface (faster flow is more effective at removing dirt of all sizes), the size of the particles of dirt, and their adhesion to the surface. These factors operate in a similar way to streams and rivers that carry or deposit solid particles of various sizes according to their rate of flow [36]. There is a relationship between the size of dirt particles, their adhesion to the surface, and the rate of flow needed to dislodge them [5]. Smaller particles of dirt adhere more readily than larger ones, and for larger particles to become lodged the surface needs to be rougher. It is evident from the inspection of windows that large quantities of fine dirt will adhere to very smooth surfaces; once adhered, the small particles need a rapid rate of flow to dislodge them.

The roles of geometry and material properties in the flow of water on surfaces are considered in more detail in the following sections.

2.2 A Collection of representative effects

Now that we have examined the basic mechanisms of flow and staining, in this section we will describe a few of the most representative effects.

- **Partial flow.** The phenomenon of *partial flow* occurs because different parts of objects receive varying amounts of incident water. This is very important for the problem of staining. The exposed parts of an object become saturated first, so that flow starts from them and proceeds onto dryer areas below. These surfaces absorb a proportion of the water until they too have a rate of incidence that exceeds the rate of absorption. In a given period of rain there is a physical point on the surface where the run-off stops due to absorption. The position of this point depends on the factors described above. The critical aspect of this from the point of staining is that it is near this point that any dirt picked up by the run-off water is redeposited [14]. Plate 1a shows a typical example of partial washing on a wall of moderate exposure. In particular, the window sills and projections above the windows serve to concentrate the runoff on both sides of the windows.

- **Differential flow.** While the variations in washing and deposition of dirt are the primary causes of staining, most of the former arise from *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 or rust stains from other corroded metals such as iron. Plates 1c and 1d depict examples of differential flow. In Plate 1c the circled region shows the spilt-milk effect caused by the deposits from a limestone window sill. In Plate 1d the circled region shows an example where rust from an iron chain has been washed onto a street below.

- **Splashback.** Splashback is a phenomenon that occurs at the base of a building where it meets the ground. Here, water hits the ground adjacent to the building and causes dirt from the ground to be picked up and deposited at a short distance up the wall. This effect also occurs when water hits horizontal ledges higher up in a building. The circled region of Plate 1b shows an excellent example of splashback at the base of a building.

- **Runoff.** An interesting aspect of runoff occurs when a non-absorbent surface is adjacent to a porous surface. In this case, the staining is limited to the porous material. In Plate 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.

- **Saturation staining.** In areas that become saturated for long periods of time, *saturation staining* often occurs. Saturation may arise from direct exposure to rainfall or concentrated runoff. 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. The circled region of Plate 1f illustrates saturation staining. Here, water collects on the ridge at the base of the building.

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

- **Disfigurement.** While flows often produce an attractive patina of age on surfaces, they sometimes cause *disfigurement*—unsightly changes to a surface; these are usually due to poor engineering. In Plate 1e, the disfigurement is quite noticeable, as the flow has caused uneven washing and saturation staining.

3 Flow Model

The goal of our model is to qualitatively capture many of the flow effects described in the previous section. Although the basic laws of physics governing fluid motion have been well studied by applied mathematicians and physicists, the precise causes of the many complex patterns and motions of a fluid flowing over a complex surface is still not well understood [1]. Moreover, since our primary goal is in the effects created by the flows over time, and not the precise nature of the water motion itself, a qualitative model of flow is sufficient for this study. Finally, the model must also account for the transport of surface materials such as dirt and soot via absorption and deposition.

Our flow model is based on particle systems and rate equations. Particles are used to model water ”droplets” both on the surface and in the air. Equations of motion describe the motion of the particle over the surface accounting for gravity, friction and the influence of obstacles. The quantity of water in a particle may increase from rain or other sources, and decrease through evaporation into the atmosphere or absorption into the base material of the surface. Surface material may also be dissolved in a particle, carried along with the water particle to a different location, and subsequently deposited there. This model is simple conceptually, is easy to implement, and only requires modest computation.

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 1. They include the mass or volume of the particle, as well as positional attributes. Each particle also carries a set of dissolved materials.

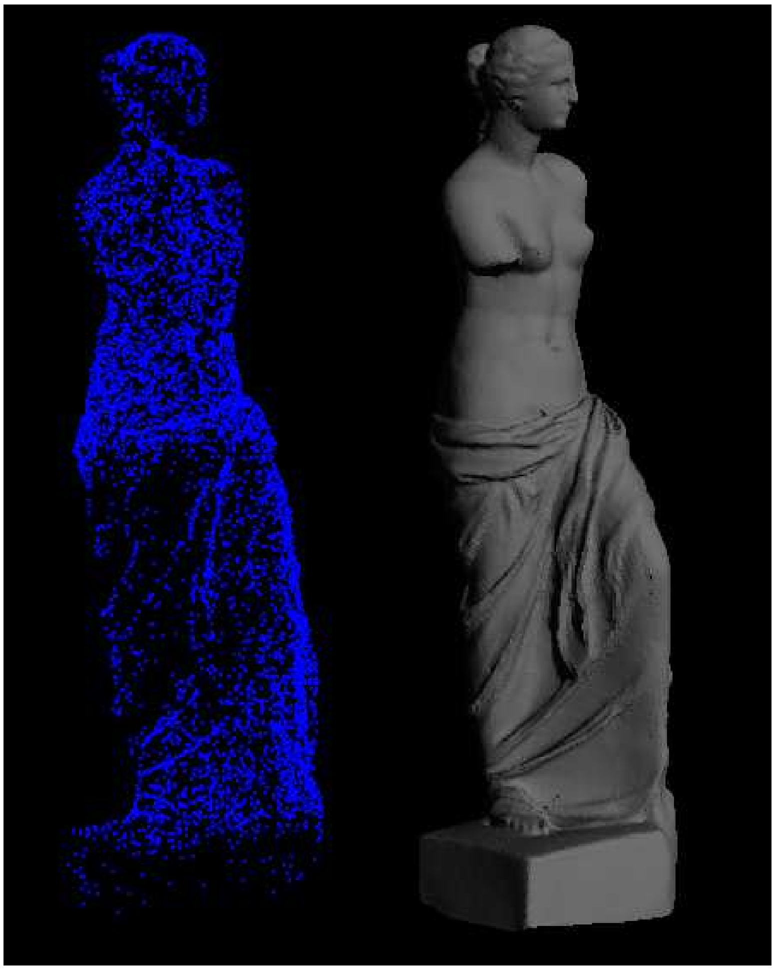

Figure 4: Particle simulation on a complex model.

The particles move along the surface as well as through the atmosphere according to a set of forces. The set of forces includes gravity, friction, diffusion, and constraint forces. Particle systems have been used widely in computer graphics and the techniques we use for modeling their motion are well described in the literature [28, 32].

Water particles fall on the surfaces of the geometric model from the atmosphere according to various distribution functions that depend on the prevailing wind direction and other features the roughly simulate rainfall. Often we precompute the number of particles hitting each portion of the surface and store it in an exposure map.

When on a smooth surface the motion of the particle is constrained to lie on the surface using the techniques described in Turk [28].

To model the effects of secondary flow particles may fall off the surface if the angle between the velocity vector and the surface tangent exceeds a critical angle. When a particle looses grip of the surface, it falls under the influence of gravity until it hits another

Water Particle Attributes	
Attribute	Notation
Mass	m
Position	x
Velocity	v
Dissolved material i	S_i

Table 1: Particle attributes.

surface. This is done by determining the point of intersection, and the corresponding intersection time. Flow past obstacles is simulated using a probability function based on the difference between the surface normals between subsequent time steps. This function determines whether a particle is to continue straight ahead or to ricochet backwards from an obstacle.

The effects of varying rates of flow can either be taken into account by adjusting the number of particles in the simulation, or by modifying the mass, and hence velocity, of the individual particles.

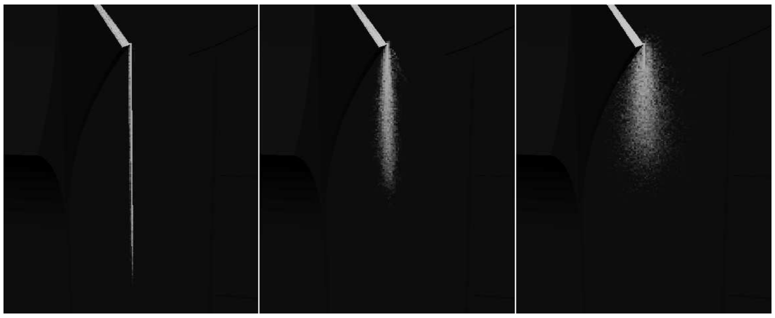

Figure 5: The effects on the flow due to surface roughness. The three figures are generated by increasing the surface roughness: the surface of the left is smoothest, the surface on the right is roughest.

The roughness of a surface also plays a role in the flow process, as illustrated in Figure 5. Particles flowing on a smooth surface move downward under only the influence of gravity and friction. On a rough surface the particles are subjected to lateral forces which cause them to disperse. These effects are modeled by a diffusion process. Each particle is subjected to a random force in the tangent plane to the surface; by varying the magnitude of the displacement, the effects of roughness are easily simulated.

This simple model of particle motion is able to reproduce many of the complex flow effects seen on surface. Roughness changes the look of flows on different surfaces. Complex flow patterns arise naturally by both constraining particles to 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. Examples of all these effects will be shown in the results section.

Surface Representation			
	Representation	Properties	Notation
Geometry	Parameterized surfaces	Area	A
		Roughness	r
Water	Texture maps	Absorptivity	κ
		Saturation	η
		Runoff function	f_{runoff}
Material	Texture map	Diffuse color	C_d
		Specular color	C_s
		Shininess	s
Deposits	Texture maps	Diffuse color	C_d
		Adhesion	α_i
		Solubility	β_i
		Concentration of material i deposit	D_i

Table 2: Surface attributes are divided into four main categories: those due to geometry, those that affect water particles, those that affect the base material, and those that affect material deposits.

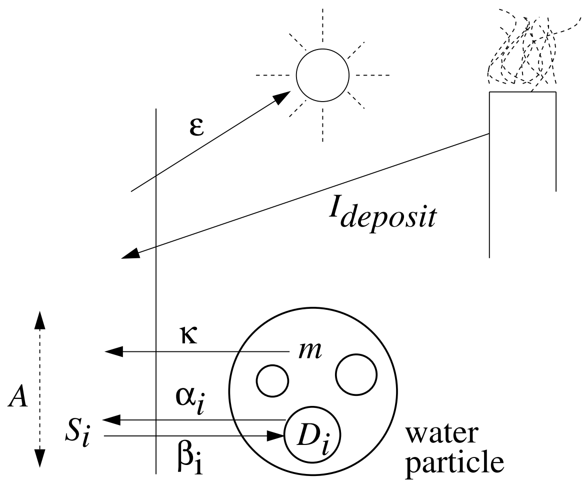

Figure 6: Absorption and sedimentation processes.

Sedimentation Process	
Parameter	Equation
Absorption	
Particle mass	$\frac{\partial m}{\partial t} = -\kappa(1 - f_{runoff}(\eta))(A/m)$
Surface saturation	$\frac{\partial \eta}{\partial t} = \kappa(1 - f_{runoff}(\eta))(m/A) - \varepsilon I_{sun}$
Sedimentation	
Dissolved material concentration	$\frac{\partial S_i}{\partial t} = -\alpha_i S_i + \beta_i D_i(m/A)$
Surface deposit concentration	$\frac{\partial D_i}{\partial t} = \alpha_i S_i(A/m) - \beta_i D_i + I_{deposit_i}$

Table 3: Sedimentation equations.

3.2 Surface Material Model

For our analysis, it will be convenient to divide the various attributes of surfaces into four main categories: geometry, base material, loose deposits, and water (see Table 2).

The geometric description of surfaces is specified as collections of patches. Each patch defines a parametric surface. The current system has two types of patches: polygons and cubic b-spline patches. It stores adjacency information between all the patches in order to allow particles to flow continuously across a patch boundary.

Each parametric surface has an associated set of texture coordinates that are used to index texture maps containing various material properties. To account for slight variations in the surface area covered by the texture samples, the area corresponding to each texture sample point is also stored in a texture map.

The materials forming the surfaces are described by the attributes shown in Figure 2. The material parameters control two processes: the rate of absorption of water by the surface, and sedimentation of each type of potential deposit. These are shown diagrammatically in Figure 6. Both the absorption and the sedimentation processes result from the interaction of a water particle with the portion of the surface immediately under it. These in turn are controlled by a set of coupled differential equations (see Table 3).

3.3 Absorption Model

The absorption model controls the interaction of water with the surface. Three parameters control the absorption: *absorption*, *absorptivity*, and *saturation*. Absorption is the maximum amount of water that the surface may take up, 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 is the product of the absorbtivity and the duration of exposure, but is limited by the absorption. This effect can be modeled by adjusting the absorptivity as a function of the saturation. This process is shown in Figure 6 and Table 3.

The quantities absorption and absorptivity are derived quantities, and not fundamental properties of matter. They are governed by the *porosity* of the material, which is defined as the percentage of the volume that is occupied by pores or void space; the distribution of the pores, their structure, and orientation are also relevant [2].

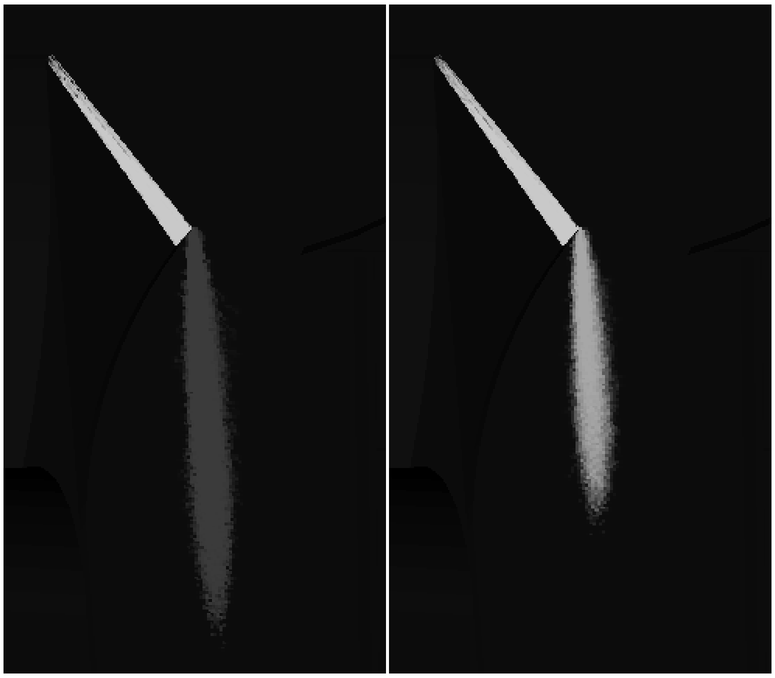

Figure 7: The effects on the flow due to absorption of a porous surface. The two figures represent two surfaces with different absorptions. Because the surface on the left has a lower absorption than the one on the right, it reaches it maximum saturation sooner and water starts to run off. As a result water flows further on the surface on the left.

The absorption of water by the surface plays a major role in the flow process, as illustrated in Figure 7. Surfaces that absorb water readily limit the extent of the flow. The quantity of water absorbed is stored in a saturation map for all points on the surface. This saturation map may be used to modulate the appearance of the surface, since water tends to make materials darker.

As a water particle moves across a porous surface, its mass will decrease due to absorption and evaporation. When the mass of the particle falls below some threshold, it "dies" and is removed from the simulation.

3.3.1 Sedimentation Model

The last main category of surface attributes control sedimentation. In the following, deposits will denote substances, such as dirt, rust, concrete dust, that ultimately will reside above the base material of the surface. The main properties of dirt particles that affect their retention on a surface are their size and adhesion [36]. The relevant properties of the surface are its surface texture, and its specific adhesion to typical dirt particles. Generally porous materials with an open pore structure retain more dirt than non-porous examples [14].

In our model, these sedimentation characteristics are captured by two parameters: *solubility*, describing the rate at which surface deposits are picked up by rain water, and *adhesion*, specifying the rate of redeposition from water particles towards the surface. These parameters may be different for different materials.

The sedimentation process is shown diagrammatically in Figure 6 and the equations governing the process are shown in Figure 3. The first equation describes the dissolving of material by a water particle; the second equation describes the deposition of material from the particle. 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 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 changes, the concentration of materials also changes. Thus, for example, as water evaporates, the dissolved material will naturally be deposited on the underlying surface.

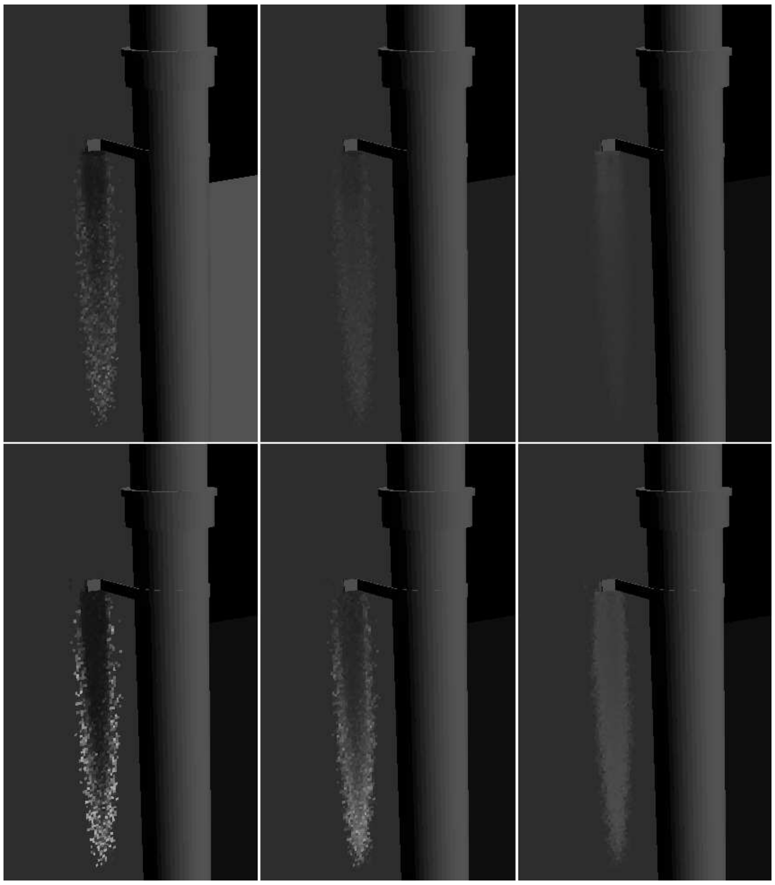

Figure 8: The relationship between solubility and adhesion. See text for details.

Environment attributes	
Attribute	Notation
Incident rain	I_{rain}
Incident sunlight	I_{sun}
Incident deposit	$I_{deposit_i}$
Evaporation	ε

Table 4: Environment

Figure 8 illustrates the sedimentation process. The figure shows stains arising from different solubility and adhesion parameters for a constant surface material and flow rate. The two rows correspond to low and high solubility and the columns to increasing adhesion. A highly soluble deposit tends to form longer and more regular streaks than a deposit with a lower solubility. A deposit with a low adhesion parameter (left) will get washed away by the water and redeposited near the edges of the flow, while a finer grained deposit and more adhesive deposit is more prone to be redeposited and thus form more uniform stains near the source. The combination of these two effects causes the common pattern of a differential stain.

The relative solubility and adhesion of deposits on a surface plays a major role in the generation of stains. When water dissolves particles, 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. More examples of this will be shown in the results.

3.4 Environmental conditions

In the absorption and sedimentation equations from Section 3.3, there are various external functions that depend on the environment. The external factors are shown in Table 4. This section surveys the primary environmental factors.

As described in Section 3.1, the rate of incident rain seeds the particle flow process. 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. More complicated models of wind could easily be incorporated into our system.

In the current system, the distribution of sunlight controls the evaporation. This in turn depends on the total solar irradiance, both due to the sky and the sun itself. In the experiments performed in this paper, the evaporation is constant on the surface.

Finally, the surface deposits are set by selecting patches and setting their concentrations to an initial value.

4 Interaction

Given some 3D model, the first step in our approach is to assign materials to surfaces. For this purpose, our system provides a library containing porosity parameters for common surface materials, such as bricks, concrete, and glass, and deposits such as rust and soot. The user controls the appearance of the model by modifying the parameters of the various materials and deposits. The effect of changing some of the most important parameters can be seen in Figures 5, 7,and 8.

Figure 9 illustrates the process of specifying materials and deposits. In the example, the user has selected the bronze material from the material library. In the material editor, the default high level parameters for bronze are shown, and the deposit editor (right) shows the initial concentrations of various deposits for this material. This particular bronze object is heavily soiled with dirt and soot, and also has a layer of patina (the static attribute says that this particular deposit should not be affected by the simulation). The default solubility and adhesion parameters for dirt are shown in the lower part of the deposit editor.

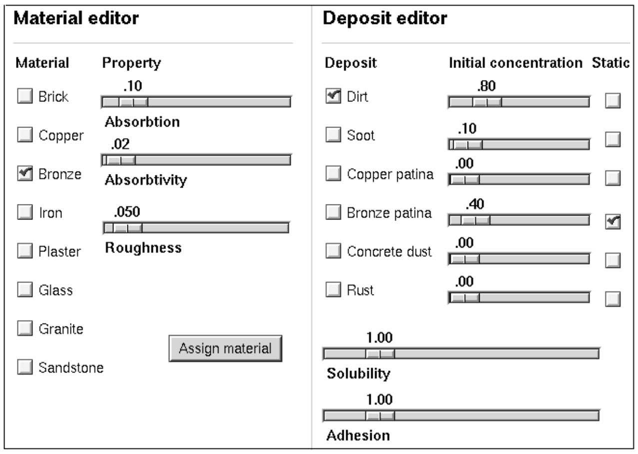

Figure 9: The material editor.

Simulations can be run globally by running the flow system on an entire model. Alternatively, the simulations can be directed by the user to run locally on a small portion of a model. The motivation for supplementary local simulations is to allow the artist to modify certain effects without having to rerun the entire simulation. The results of local simulations are stored in layers that can be combined to form a composite appearance at any time. Also, local simulations provide fast feedback on the appearance of specific regions and effects of particular interest, which is important for some applications. Figure 10 shows a characteristic staining pattern generated in a couple of minutes by a local simulation. A corresponding global simulation might take hours to create such effects; thus, local modifications are a highly desirable supplement.

Aside from control over the porosity and sedimentation models, the system allows parameters in various other modules to be changed, including the intensity of the rain, position

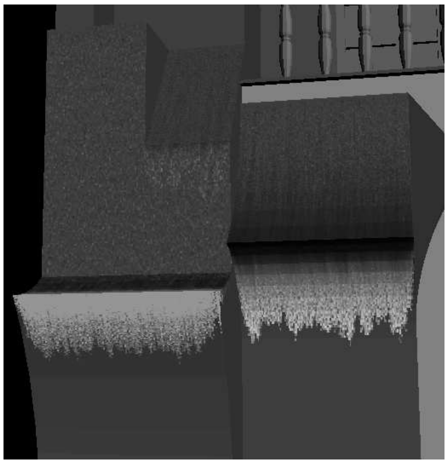

Figure 10: Example of a local simulation.

of the sun and gravity.

From an artistic point of view, the technically correct appearance of an object may not always be the desired one. As an example, suppose a production artist would like the region of a brick wall below a window sill to have an interesting staining pattern for a closeup shot, but the sill prevents rain water from ever getting to that area. One way of resolving this stalemate could be to go back to the modeling stage and modify the geometry, but it appears that the ability to override physical correctness in important special cases would be useful in any physically inspired texturing system. To demonstrate this idea, our system provides a heuristic that allow particles within a given radius of influence to a nearby wall to attach to the wall instead of dropping off the surface. This simple feature has proven to be very convenient for controlling the simulations without having to make changes to the underlying geometry.

Please refer to the videotape.

5 Results

In this section we show results for two complex models: a building and a statue.

5.1 Building Model

Plate 2 shows a variety of flow effects on a building facade. For comparison, Plate 3 shows side-by-side renderings of the building, with and without the flow effects. 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. Eight particle runs were used to create the effects, using a combination of global and local runs.

In the center section of the building alongside the main window, there are several examples of partial flows that continue onto 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 difference in roughness and adhesion of the surface. On the vertical panels to the left of the yellow brick section, there is evidence of saturation staining at the top of the panel as it begins to curve out. On the stone at the base of the building, there are subtle splashback effects making the lower part even dirtier. 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 is shown on the copper rain pipe on the left side of the building.

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 RenderMan shading language. Plate 4 shows several of the textures associated with one patch (bright areas indicate high concentrations of deposits). In this plate, (4a) is the color texture; (4b) is the saturation texture. Below these are the deposit maps: (4c) is dirt, (4d) is soot, and (4e) is copper patina. To produce the final images, the color of the deposit layer is computed 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. 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.

5.2 Venus de Milo

Plate 5 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 91,000 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. All the effects are the result of global simulations.

The lower 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 upper left 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. Note the nice non-uniform pattern of dirt (unfortunately some contrast has been lost in the printing process.) The pattern is still uniform on the base of the statue and areas closest to the ground, since the water did not reach that section. There are noticeable streaks in the dirt patterns due to the flow, and a randomness due to the individual nature of each particle. These dirt patterns are especially apparent in the left image. Dirt accumulates in various parts of the statue where the surface is protected from the path of the flow, such as under the arms. The dirt texture conforms to the folds in the fabric below. Note that on the right image, the upper surfaces of the convex parts of the folds are clean; the lower surfaces are dirty. It is not possible to achieve these effects with simple accessibility [15]. The image was rendered using a diffuse model for the marble, and the dirt layer composited using the same technique as for the building.

The upper middle and lower right images show the direct effect of water poured over the head of the statue. Most of the water is absorbed on the upper part of the model and does not travel down to the base. It is interesting to notice how the flow conforms to the smooth contours of the statue. To render both these images, the saturation map is used to darken the color of the base material and deposits as a function of the amount of water present. In the lower right image, we add a specular term where water is present on the surface. This is to simulate the effect of water glistening on top of the statue, such as just after after a rain storm. This effect is rather exaggerated in this particular rendering to compensate for the fact that only a single point light source is being used.

6 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 them. 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, and could be used as a basis for the creation and design on other complex patterns on these surfaces.

Normally rendering consists of a local process, reflection of light from a surface, and a global process, interreflection of light between surfaces. This work shows the importance of global processes in determining the reflection function of an object. Thus, the idealized reflection models used in computer graphics are not sufficient to capture a wide range of appearances.

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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