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# Porous Flow and Sediment Transport Simulation for Physically-Based Weathering

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**Figure 1:** Coffee is dissolved in the water that gets inside the filter. Concentrated water then seeps through the filter to reach the glass. From left to right: Render of the scene, solid and wetting, fluid and its contained sediments, sediments density.

## Abstract

In the graphic community, rendering lifelike scenes remains an open challenge. Among the features required to reach photorealism, aging is the crucial detail that breaks the pristine aspect that is rarely observed in real life. Multiple approaches have been proposed, from example-based to physical simulation, to compute the aging of an object. In this context, we present a simulation framework that handles multiple weathering effects causing an object to alter over time. We identify the key phenomena (wetting, drying, erosion, deposition, and dissolution) and propose a base framework to address the aging process. To tackle this challenge, our method adapts a Smooth Particle Hydrodynamics model to represent external fluids (i.e., classical fluid simulation) and internal porous flow. Our framework handles the wetting, drying, and flow in the porous space in a unified approach. We extend pre-existing sediment transport method to allow the sediment transport outside and inside the porous space. With our method, sediments can be eroded from a solid surface, transported across solid objects through their porous space, and deposited to modify other objects' properties across the scene.

## 1. Introduction

As stated by Becket and Badler [BB90], an ideal renderer cannot produce realistic imagery if the virtual scene only exhibits pristine objects. In real life, appearances of objects are constantly modified by their surrounding environment. Those modifications can be reversible (wetting, dust deposition, deformations, etc.) or definitive (cracks, scratches, rust, etc.). Aging can impact many of the properties of the objects (geometric, chemical, optical, mechanical) and should always be considered when rendering a photorealistic scene.

Usually, geometries and/or textures are authored manually to emulate those appearances modifications. However, dealing with the complexity and the number of underlying phenomena is a time-consuming and challenging task, leading to heavy manual authoring requiring advanced physical knowledge.

Dorsey et al. [DRS07] classified the processes affecting appearance in three categories: mechanical, chemical, and biological. As each process can affect several properties of the material, Merillou and Ghazanfarpour [MG08] classified them with a phenomenolog-

1 ical approach. In the same way, we identified that most appearance  
 2 changes are due to the simultaneous interactions between elemen-  
 3 tary phenomena. Based on previous works, we highlight a set of  
 4 phenomena that are key to tackling the aging problem:

5 **Deposition:** Deposition is a process where a deposit of matter is  
 6 left behind after the interaction between a surface and a fluid carry-  
 7 ing micro-particles. Deposits cover the initial surface and affect  
 8 the object’s albedo, geometry, and physical properties. They can  
 9 accumulate to create durable volumes of matter or be cleaned off  
 10 by further fluid interactions. See **A** in Fig. 2.

11 **Dissolution:** When an object interacts with a fluid, part of the  
 12 matter can pass into the fluid phase. This reaction affects geometry  
 13 and the albedo/light absorption of the solvent. See **B** in Fig. 2.

14 **Erosion:** Erosion is a generic concept where fluid interactions  
 15 alter the surface. It can be a direct consequence of dissolution or  
 16 mechanical interactions between the object and the fluid. In this  
 17 article, we consider erosion as a mechanical phenomenon. See **C** in  
 18 Fig. 2.

19 **Chemical reaction:** A chemical reaction occurs when reactants  
 20 interact to form new products. When fluids and/or solids get in con-  
 21 tact their chemical compositions are altered, thus modifying their  
 22 physical properties, albedo, and geometry. See **D** in Fig. 2.

23 **Organic growth:** Fluids transport seeds or spores. Those can  
 24 take root object surfaces or within the porous space. External fac-  
 25 tors may activate plant growth (temperature, moisture, illumina-  
 26 tion). In addition, roots create internal stress, which deforms the  
 27 host object and creates new geometry. See **E** in Fig. 2.

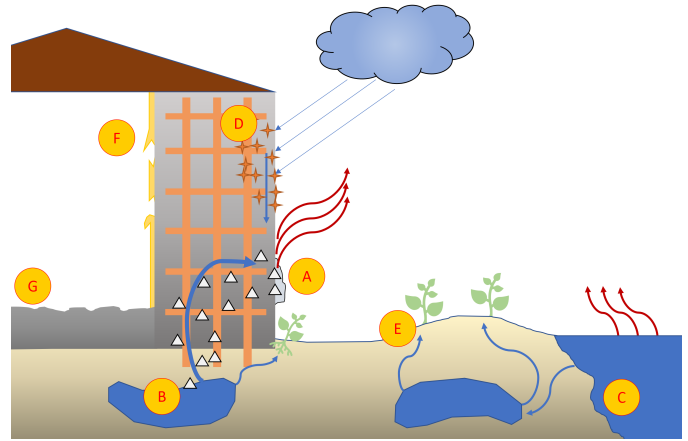
28 **Deformation, cracks and peeling:** When a material undergoes  
 29 regular environmental changes such as variations in temperature  
 30 or moisture level, its properties can be altered. Depending on the  
 31 material, the frequency, and the magnitude of these changes, defor-  
 32 mations may occur and create cracks or peelings in the case of thin  
 33 layers. See **F** in Fig. 2.

34 **Impacts and scratches:** Mechanical interactions between ob-  
 35 jects can introduce surface alteration at different scales. Both mi-  
 36 croscopic scratches and collision-induced impacts change the sur-  
 37 face geometry. More pernicious interactions can cause damage to a  
 38 material’s protective layer, thus allowing the intervention of other  
 39 phenomena (e.g., impact on a car paint removing rust protection of  
 40 the underlying metal). See **G** in Fig. 2.

41 All the previously described phenomena strongly correlate with  
 42 the transport of matter both inside the objects (due to porosity) and  
 43 on their surfaces. Moreover, they interact through this matter flow,  
 44 making the aging process of very complex systems challenging to  
 45 model accurately. Indeed, changing the behavior of any part of the  
 46 process may impact the flow and change or even prevent any aging  
 47 phenomenon from occurring.

48 In this paper, we propose to address these issues by introduc-  
 49 ing a framework that can handle both temporary phenomena (such  
 50 as wetting and evaporation) and definitive flow-based phenomena  
 51 which do not dissipate without leaving a trace. In summary, our  
 52 main contributions are:

- A generic simulation framework that can handle multiple phe- 53  
 nomena simultaneously such as wetting and evaporation of water, 54  
 erosion and dissolution of a solid material leading to the crea- 55  
 tion, transport and deposition of micro-particles from the initial 56  
 object; 57
- An authoring pipeline to simulate the aging process of a pristine 58  
 scene to achieve a plausible, realistic weathered counterpart; 59



**Figure 2:** Example scene featuring multiple weathering phenomena. **A:** Deposition or crystallization of salts at the building surface. **B:** Salt dissolution in the groundwater reservoir and its transport to the surface. **C:** River bed erosion. **D:** Corrosion of iron rods in armed concrete and transport of iron oxide to the surface through moisture. **E:** Organic growth favored by sun exposition and soil moisture level. **F:** Wall paints peeling due to humidity within the wall. **G:** Impacts and scratches on the floor.

2. Previous Works 60

61 Reproducing realistic and complex weathered appearances is a  
 62 challenging and trending task in computer graphics. As weathered  
 63 appearances result from several concurrent physical phenomena,  
 64 such a goal can be achieved either by the simulation of the under-  
 65 lying physical processes or through the direct synthesis of the final  
 66 appearance using various input data guiding the synthesis.

Imaged Based Methods 67

68 Leveraging the inherent correlation between appearance and  
 69 weathering phenomena, most of these methods compute a weather-  
 70 ing degree map from appearance variations in input photographs or  
 71 3D scans. Explicit manipulation of the map provides artistic con-  
 72 trol over the result and allows for appearance transfer and arbitrary  
 73 weathering or de-weathering of similar surfaces. The final appear-  
 74 ance is then synthesized by reprojecting the corresponding visual  
 75 content accordingly to the map.

76 By taking advantage of the non-uniformity of the weathered ap-  
 77 pearance of an otherwise uniform pristine object, an appearance  
 78 manifold linking weathering phenomena and visual content can  
 79 be built [WTL\*06] to guide appearance synthesis. To absolve the  
 80 method from heavy lighting restrictions in the capture process, Xu

1 et al. [XWT\*08] propose to split the input photograph into re-  
2 flectance and illumination component. The appearance manifold  
3 extracted from the input image is used to generate both the weather-  
4 ing degree and shading maps. After editing the weathering degree  
5 map, (de)weathered appearance can be synthesized by searching  
6 for the best candidate in the appearance manifold matching both  
7 weathering degree and lighting conditions. It also details how to  
8 transfer appearance between two pictures, successfully transform-  
9 ing corrosion present in a photo into organic growth extracted from  
10 another example.

11 Because appearance manifolds can be costly to construct, Ban-  
12 deira and Walter [BW09] proposed to use an appearance map based  
13 on the Lab color space to alleviate the (de)weathered pixel color  
14 search. Bellini et al. [BKCO16] tackled the appearance synthesis  
15 of manufactured structures by exploiting the regularity of patterns  
16 found in those structures. Through the use of texture analysis, Lu,  
17 Dorsey, and Rushmeier [LDR09] extracted content-aware patches  
18 from input exemplars. Those are then distributed on a new texture  
19 to reproduce the input's spatial distribution and mesoscopic details.

20 By taking into account the correlation between local geometry  
21 and object appearance, a guidance map can be extracted from an  
22 input textured mesh [MKC\*06,LGG\*07]. Using this guidance map  
23 and a spatially varying texture synthesis model, the input mesh ap-  
24 pearance can be mapped to another one. This automatic process  
25 removes the manual authoring of the weathering distribution map.

## 26 Physically Based Simulations

27 Several simulation-based approaches were proposed to accurately  
28 model and reproduce the weathering effect. The patina formation,  
29 for instance, can be simulated by combining the use of heightmaps  
30 and basic morphological operators to thicken or erode micro ge-  
31 ometric surface details [DH96]. Following the idea of Dorsey et  
32 al. [DPH96], Chen et al. [CXW\*05] proposed a generalized model  
33 of interaction between particles and surfaces that can represent  
34 multiple material property changes allowing stains, erosion, corro-  
35 sion, and dirt deposition. While maintaining a good level of artistic  
36 control, this approach does not guarantee physically accurate re-  
37 sults.

38 Dorsey et al. [DEJ\*99] simulate the water flow that occurs in  
39 porous stones to tackle object aging. This approach lies on an eule-  
40 rian simulation scheme computed in small cubic volumes aligned  
41 with the object surface called slabs. This method supports erosion,  
42 deposition, and sediments transport within and between the slabs.  
43 The underlying simulation data structures allow precomputing sub-  
44 surface scattering. While this approach guarantees physically plau-  
45 sible results, it is limited to stones. In addition, the method requires  
46 a quad mesh representation to place voxels slabs correctly.

47 Estimating the fluid flow both inside and outside the materials  
48 pore space has been studied [LAD08]. Using Smooth Particle Hy-  
49 drodynamics (later referred to as SPH), authors proposed a method  
50 supporting two-way coupling and elastic bodies to exhibit realistic  
51 wetting and deformations under pressure.

52 Wojtan et al. [WCMT07] proposed a method to compute ani-  
53 mations of natural phenomena such as erosion, sedimentation, and

acidic corrosion. Solids are represented using a level set stored in  
54 regular grids distinct from the grid used for fluid simulation. Level-  
55 set grids are then used to update the physical properties of solid  
56 objects.  
57

58 Kristof et al. [KBKS09] use SPH to simulate hydraulic ero-  
59 sion, transport, and deposition of sediments on heightfield terrains.  
60 While limited to this representation, their approach produces real-  
61 istic river beds and adds details to the terrain reliefs.

62 With both particle simulation and appearance manifold, Bosch  
63 et al. [BLR\*11] proposed a hybrid approach. They combine ex-  
64 tracted stains color and distribution information from a captured  
65 photograph [XWT\*08] and a user-defined proxy mesh to produce  
66 a set of parameters driving a particle-based simulation capable of  
67 reproducing such appearance alterations. The particle simulation is  
68 then applied to novel virtual scenes.

69 Cracks and peeling on a planar surface can be estimated us-  
70 ing [PPD02]'s method. By decomposing the surface into two lay-  
71 ers, cracks and peeling are simulated using a 2D grid. A 3D mesh  
72 of the resulting peeled paint layer is then extracted. The process al-  
73 lows cracks to be user-defined via an input texture. However, this  
74 approach is limited to planar surfaces and does not take into ac-  
75 count paint thickness.

76 Merillou et al. [MMGG12] investigated building degradations  
77 caused by salt decay. They proposed a model based on user-  
78 defined input textures to identify material's characteristics, such  
79 as albedo, porosity and salt concentration. By combining the pro-  
80 cedurally computed crystallization depth and external atmospheric  
81 conditions, the model generates an aging-location texture. The lat-  
82 ter is interpolated during rendering to alter material albedo or  
83 heightmaps.

84 Huber et al. [HPS11] proposed a liquid diffusion model in porous  
85 textiles based on SPH and a discrete cellular automaton to compute  
86 the various diffusion states. Interactions between hairs and water  
87 were also studied by Rungjiratananon et al. [RKN12]. They pro-  
88 posed using an eulerian grid to simulate the fluid diffusion within  
89 hairs where strands are modeled using connected lagrangian parti-  
90 cles. Dripping is also taken into account when grid cells are over-  
91 saturated. Patkar et al. [PC13] proposed to model the wetting of  
92 porous solids by simulating liquid absorption, diffusion, and drip-  
93 ping on a tetrahedral mesh. While supporting mesh deformation  
94 and allowing two-way coupling between solids and fluids, advec-  
95 tion is neglected.

96 Rungjiratananon et al. [RSKN08] proposed a model to tackle  
97 wetness propagation in granular materials. The latter is simulated  
98 using a combination of discrete element methods for granular mate-  
99 rials and a SPH fluid simulation handling surface tension between  
100 granular particles. Mechanical interactions between granular ma-  
101 terials and liquids have been recently studied and modeled using  
102 Material Point Methods by Gao et al. [GPH\*18].

103 Recently, Munoz et al. [MPBM\*18] proposed a method to model  
104 the pollution accumulation on building facades. Given a 2D map of  
105 the city and its pollution sources, such as traffic roads, a 2D Lattice-  
106 Boltzmann simulation is computed to obtain a wind map. This map  
107 is then used to compute a pollution map which stores the pollu-  
108 tion propagation in the 2D scene. During rendering, they combine



1 screen-space techniques and material properties to estimate multiple factors which affect the final appearance such as insolation, pollution, porosity, wind accessibility, sky accessibility and rain accessibility.

2 As seen above, all these approaches commonly share the tendency to only tackle specific aging effects or to simulate a small number of them in a restricted context. However material appearance is not only affected by a specific phenomenon but by a joint intricated interaction of multiple weathering effects. In this paper, we propose a framework for the simulation of aging phenomena based on the computation of the fluid flow inside and outside the objects volume enabling the transport of sediments and solute through porous networks. It relies on Smoothed Particle Hydrodynamics which is a commonly used concept for solving numerical simulations of continuum mechanics. We refer the reader to an extensive state of the art of SPH-based methods [KBST19]. We present a comprehensive model handling: erosion, dissolution, deposition and evaporation as the combination of these phenomena are responsible for full changes in appearance.

### 20 3. Framework

21 Our model relies on a particle-based simulation using SPH continuum equations. As we want to correctly model interactions between fluids and solids, we distinguish two types of particles: fluid particles to model external fluid and solid particles to model inner fluid interactions through material pores, the latter embedding material-related fields such as porosity, permeability, capillary potential. All these particles  $p_i$ , centered at position  $\mathbf{x}_i$ , with a mass  $m_i$ , a density  $\rho_i$  (hence a volume  $V_i = m_i/\rho_i$ ) are used to sample continuous properties (such as porosity, water saturation, temperature, etc.). Using the following SPH continuum equations, we can sample an arbitrary field  $A$  at an arbitrary position  $\mathbf{x}$ :

$$32 \quad A(\mathbf{x}) \equiv \sum_j A_j V_j W(\mathbf{x}_j - \mathbf{x}) \quad (1)$$

33  $W(\mathbf{x}_j - \mathbf{x})$  being the standard cubic spline kernel defined as follows:

$$35 \quad W(\mathbf{x}_j - \mathbf{x}) = \frac{8}{\pi h^3} \begin{cases} 6d^3 - 6d^2 - 1 & , d \leq 0.5 \\ 2(1-d)^3 & , 0.5 < d < 1.0 \\ 0 & , d \geq 1.0 \end{cases} \quad (2)$$

$$36 \quad \text{with } d = \frac{\|\mathbf{x}_j - \mathbf{x}\|}{h} \quad (3)$$

38 In order to ease the notation,  $W(\mathbf{x}_j - \mathbf{x}_i)$  will be later referred as  $W_{ij}$ . Its gradient estimation sampled at particle  $p_i$ , noted  $\nabla W_{ij}$ , is defined as follow:

$$41 \quad \nabla W_{ij} = \frac{48}{\pi h^3} \frac{\mathbf{x}_j - \mathbf{x}_i}{\|\mathbf{x}_j - \mathbf{x}_i\| h} \begin{cases} d(3d-2) & , 0 < d \leq 0.5 \\ (-1+d)(1-d) & , 0.5 < d < 1.0 \\ 0 & , d \geq 1.0 \end{cases} \quad (4)$$

42 We can thus estimate the gradients and laplacian of a field  $A$

Symbol	Description	Unit	Phase
$i$	Particle index	—	—
$k$	Material index	—	—
$s_k$	Sediment index	—	—
$r$	Particle radius	m	—
$H$	Relative humidity	—	—
$\mathbf{g}$	Gravity	$\text{m} \cdot \text{s}^{-2}$	—
$D^{s_k}$	Sediment diffusivity	$\text{m}^2 \cdot \text{s}^{-1}$	—
$\mathbf{x}_i$	Particle position	m	Both
$V_i$	Particle volume	$\text{m}^3$	Both
$V_i^f$	Fluid volume	$\text{m}^3$	Both
$V_i^{s_k}$	Sediment volume	$\text{m}^3$	Both
$C_i^{s_k}$	Sediment concentration	—	Both
$\mathbf{v}_i^{s_k}$	Sediment settlement velocity	$\text{m} \cdot \text{s}$	Both
$p_i^c$	Capillary pressure	Pa	Both
$T_i$	Temperature	$^\circ\text{C}$	Both
$\alpha_i$	Heat diffusion coefficient	$\text{m}^2 \cdot \text{s}^{-1}$	Both
$S_i$	Pores fluid saturation	—	Both
$V_i^k$	Material volume	$\text{m}^3$	Solid
$\lambda_i$	Permeability	$\text{m}^2$	Solid
$\beta_i$	Porous stiffness	Pa	Solid
$\sigma^k$	Material stress resistance	Pa	Solid
$\Phi_i$	Porosity	—	Solid
$\tau_i$	Tortuosity	—	Solid
$r^{s_k}$	Sediment particle radius	mm	Solid
$r^{p_k}$	Characteristic pore radius	mm	Solid
$\rho_i$	Density at particle $i$	$\text{kg} \cdot \text{m}^{-3}$	Fluid
$\rho_0$	Fluid rest density	$\text{kg} \cdot \text{m}^{-3}$	Fluid
$\mu$	Dynamic viscosity	$\text{Pa} \cdot \text{s}$	Fluid
Control parameters			
$\kappa_{\text{concentr}}$	Concentration	—	—
$\kappa_{\text{depos}}$	Deposition	—	—
$\kappa_{\text{erosion}}$	Erosion	—	—
$\kappa_{\text{evap}}$	Evaporation	—	—
$\kappa_{\text{saturation}}$	Saturation	—	—

**Table 1:** Notation table. In the paper, per-particles properties are indexed using  $i$  and  $j$ . Properties linked to a material are exponentiated using  $k$ , those linked to a sediment of material  $k$  using  $s_k$  and the ones linked to the fluid using  $f$ . Control parameters permits to tune the simulation and to exacerbate specific effects as shown in the figures.

using equations (5) and (6) respectively.

$$43 \quad \nabla A_{ij} \equiv \sum_j V_j A_{ij} \nabla W_{ij} \quad (5) \quad 44$$

$$45 \quad \nabla^2 A_{ij} \equiv \sum_j V_j A_{ij} \frac{2\|\nabla W_{ij}\|}{\|\mathbf{x}_j - \mathbf{x}_i\|} \quad (6) \quad 46$$

47 We suppose the solid to be incompressible and thus can use  $V_j = m_j/\rho_j$ . However, if material compression is required, equations (1), (5) and (6) must use the mass-density ratio formulation. 49

In practice, our materials are defined by a set of properties such 50

1 as porosity, permeability, capillarity potential, temperature diffu-  
2 sivity, tortuosity (as seen in Table 1).

3 Each of our particles can aggregate several materials as needed.  
4 In such a case, their final properties are linearly interpolated ac-  
5 cording to the particle composition. This allows for the creation  
6 of complex materials as commonly found in nature (impurities in  
7 rocks or metal, for example) and reduces the number of particles  
8 needed to represent the scene. The global volume  $V_i$  can then be  
9 retrieved as the sum of the volume of each material of the solid  
10 particles.

11 Fluid particles represent both a volume of fluid and the volume of  
12 sediments they carry. As the maximal concentration of sediments in  
13 fluid particles remains low, its influence on volume variations can  
14 be safely neglected, simplifying the simulation.

15 We call "sediments" the set of properties describing the behavior  
16 of physical micro-particles contained in the fluid phase or trapped  
17 in the material pores. It can be used to represent both actual sedi-  
18 ments (particles with a radius > micrometer) or soluble (particles  
19 with a radius < micrometer). Sediment is characterized by its den-  
20 sity, diffusivity in water (solubility), the maximum concentration in  
21 water, and characteristic particle radius. Table 1 shows a compact  
22 version of all relevant data and their corresponding phases.

### 23 3.1. External Flow

24 As explained previously, we distinguish how particles behave de-  
25 pending on whether they are considered fluid or solid. Although we  
26 rely on an SPH fluid simulation to accurately model particles beh-  
27 avior, pressure acceleration, viscosity, surface tension, and bound-  
28 ary conditions must be carefully considered.

29 In practice, we rely on the pressure solver from [SP09,KBST19]  
30 to ensure incompressibility, namely preventing the fluid from con-  
31 stantly oscillating over time. Viscosity is considered fixed for the  
32 whole fluid using the standard model from [Mon05]. Surface ten-  
33 sion is handled using [AAT13]'s approach. Finally, the volume field  
34 (i.e.  $\sum_j V_j W_{ij} = 1$ ) is normalized to preserve boundary conditions,  
35 thus preventing fluid particles to get across solids.

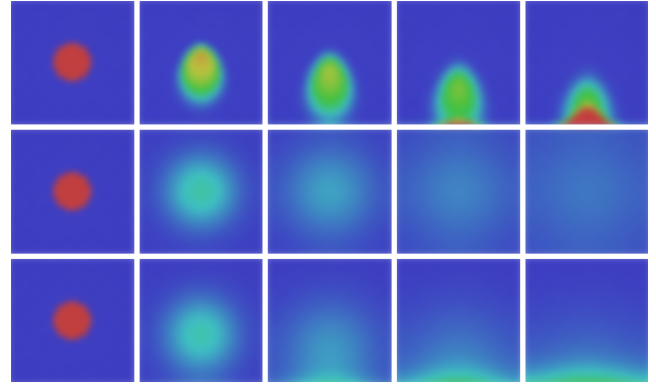
### 36 3.2. Porous Flow

37 The key component of our method is to simulate the fluid flow in  
38 porous materials. Since our liquid particles can contain sediments,  
39 this step will then allow us to model the transport of sediments  
40 through the object and, thus, more generally, the transport of matter  
41 in the scene (see Section 3.3).

42 As described in [DEJ\*99, LAD08], fluid flow traveling inside  
43 a porous medium is governed by Darcy's law [Dar56]. The latter  
44 (eq. (7)) expresses the instantaneous flux  $\mathbf{q}$  of a fluid, with a dy-  
45 namic viscosity  $\mu$  and density  $\rho$ , traveling in a porous medium with  
46 a permeability  $\lambda$ , in relation with pressure gradient  $\nabla p$  and gravity  
47 acceleration  $\mathbf{g}$ :

$$48 \quad \mathbf{q} = -\frac{\lambda}{\mu}(\nabla p - \rho\mathbf{g}) \quad (7)$$

49 The fluid velocity within the medium (later referred to as porous



**Figure 3:** A vertical slice of a solid homogeneous porous material saturated with water at its center (red disk). The heatmap shows the pore saturation in water (red is fully saturated and blue is dry). **first row:** Only the advection part is computed, **second row:** Diffusion part only, **third row:** Full computation of water flow within the porous medium

50 velocity) can be retrieved by dividing the flux by the material poros-  
51 ity  $\phi$ . While Darcy's law describes the porous flow for homoge-  
52 neous mediums, it can be piecewisely adapted to simulate flow in  
53 heterogeneous mediums. As each solid particle is defined by its  
54 properties  $\phi_i$  and  $\lambda_i$ , porous velocity can be rewritten using the  
55 SPH formalism to model the volume exchange within the medium.  
56 Porous velocity can thus be decomposed in two distinct parts: the  
57 diffusion velocity ( $\text{Diff}^f$ ) and the advection velocity ( $\text{Adv}^f$ ), re-  
58 spectively the rate at which a fluid will propagate from high to low-  
59 pressure locations and the rate at which gravity will guide the flow  
60 (see Fig. 3).

$$61 \quad \text{Diff}^f = -\frac{\lambda}{\mu\phi}(\nabla p) \quad (8)$$

$$62 \quad \text{Adv}^f = -\frac{\lambda}{\mu\phi}(-\rho\mathbf{g}) \quad (9)$$

63  
64 **Diffusion:** As stated by [LAD08], at the pore scale, the pressure  
65 applied on each particle is considered to be the capillary pressure  
66  $p_i^c$ . Its differential will drive fluid from saturated pores to lesser  
67 ones:

$$68 \quad p_i^c = \beta(1 - S_i)^{\kappa_{\text{sat}}} \quad (10)$$

69 Where  $\beta$  is the porous stiffness (or capillary potential) and  $\kappa_{\text{sat}} \in$   
70  $[0; 1]$  a constant controlling the influence of the saturation. The par-  
71 ticle saturation  $S_i$  is defined as the ratio between the fluid volume  
72  $V_i^f$  and the pore space  $V_i\phi_i$  (i.e. the void volume of the particle):

$$73 \quad S_i = \frac{V_i^f}{V_i\phi_i} \quad (11)$$

74 Since we consider the material is homogeneous and that we ex-  
75 press the capillary pressure as a function of saturation, we can ex-  
76 press equation (8) as a saturation diffusion process using the Muller

1 SPH diffusion formulation [MSKG05]:

$$2 \quad \text{Diff}_i^f = - \sum_j \frac{\lambda}{\mu\phi} (p_i^c - p_j^c) V_j \nabla^2 W_{ij} \quad (12)$$

3 When multiple materials exist in a neighborhood, their particles  
4 exhibit different properties that cannot be interpolated directly  
5 without leading to incorrect behaviors. To prevent this, we must  
6 only consider the strongest constraints. We rewrite  $\lambda/\mu\phi$  in a per-  
7 particle formulation:

$$8 \quad \eta_i^p = \frac{\lambda}{\mu\phi} = \frac{\lambda_i}{\mu} \frac{1}{\phi_i} \quad (13)$$

9 Substituting (13) in (12) to account for the maximal resistance to  
10 fluid flow (smallest  $\eta^p$ ) between particles  $i$  and  $j$  yields:

$$11 \quad \text{Diff}_i^f = - \sum_j \min(\eta_i^p, \eta_j^p) (p_i^c - p_j^c) V_j \nabla^2 W_{ij} \quad (14)$$

12 Since the diffusion is expressed as a function of the saturation,  
13 we need to transform it back to a flow rate.

$$14 \quad \text{DiffV}_i^f = -V_i^f \sum_j \min(\eta_i^p, \eta_j^p) (p_i^c - p_j^c) V_j \nabla^2 W_{ij} \quad (15)$$

15 **Advection:** To take into account fluid advection between porous  
16 solid particles, we chose to use a donor-acceptor scheme like the  
17 one proposed by Kristof et al. [KBKS09]. We identify an acceptor  
18 and a donor for each couple of particles  $i, j$ . Because we consider  
19 solid and fluid in the pore space as incompressible material, we  
20 assume that  $\rho$  is equivalent to its constant rest density  $\rho_0$  in equation  
21 (9).

22 Similarly to the diffusion velocity, we must also take into ac-  
23 count the maximal resistance to fluid flow using the minimal porous  
24 resistance between particles (using eq. (13)), thus we obtain:

$$25 \quad \text{Adv}_i^f = - \sum_j \begin{cases} V_j \min(\eta_i^p, \eta_j^p) (-\rho_0 \vec{g} \cdot \hat{\mathbf{x}}_{ij}) \|\nabla W_{ij}\| & , -\rho_0 \vec{g} \cdot \hat{\mathbf{x}}_{ij} \geq 0 \\ V_i \min(\eta_i^p, \eta_j^p) (-\rho_0 \vec{g} \cdot \hat{\mathbf{x}}_{ij}) \|\nabla W_{ij}\| & , -\rho_0 \vec{g} \cdot \hat{\mathbf{x}}_{ij} < 0 \end{cases} \quad (16)$$

26 Where  $\hat{\mathbf{x}}_{ij}$  denotes the normalized vector between particles  $i$  and  $j$   
27 (i.e.  $\frac{\mathbf{x}_j - \mathbf{x}_i}{\|\mathbf{x}_j - \mathbf{x}_i\|}$ ). Similarly to equation (15), we transform the velocity  
28 to a flow rate and simplify the formulation:

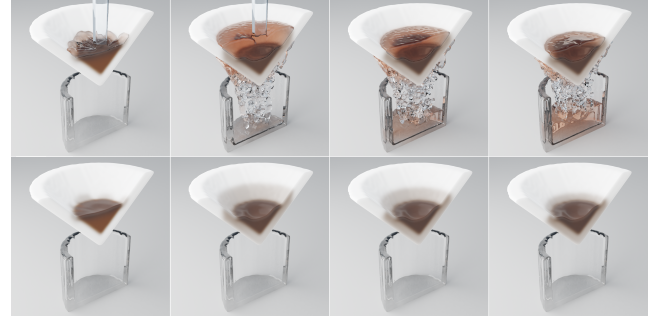
$$29 \quad \text{AdvV}_i^f = \sum_j \begin{cases} V_j^f V_j \min(\eta_i^p, \eta_j^p) \rho_0 (\vec{g} \cdot \hat{\mathbf{x}}_{ij}) \|\nabla W_{ij}\| & , \vec{g} \cdot \hat{\mathbf{x}}_{ij} \leq 0 \\ V_i^f V_i \min(\eta_i^p, \eta_j^p) \rho_0 (\vec{g} \cdot \hat{\mathbf{x}}_{ij}) \|\nabla W_{ij}\| & , \vec{g} \cdot \hat{\mathbf{x}}_{ij} > 0 \end{cases} \quad (17)$$

30 The final fluid volume variation at a given particle  $i$  is obtained  
31 by combining the diffusion and the advection part:

$$32 \quad \frac{\partial V_i^f}{\partial t} = \text{DiffV}_i^f + \text{AdvV}_i^f \quad (18)$$

### 33 3.3. Sediment Transport

34 In a porous medium, sediments carried by fluid in the pore space  
35 get slowed down due to interaction with the pore's surface. As such,  
36 computing the water flow is not the only requirement to compute  
37 the sediment flow in such materials. Sediment transport in fluid,



**Figure 4:** Cut view illustrating dissolution of coffee passing through a porous medium following water flow. **Top row:** Render of water, solid, and sediment. **Bottom row:** Only solid surface is shown illustrating the dissolution process.

much like water movement in a porous medium, is affected by dif-  
fusion and advection components. The problem can thus be split as  
we previously did in Section 3.2.

Following [MSKG05], diffusion of an attribute  $A$  in a fluid in  
relation with its diffusion coefficient  $D$  can be expressed as follow:

$$41 \quad \frac{\partial A}{\partial t} = D \nabla^2 A \quad (19) \quad 42 \quad 43$$

44 In our case, the volume variation of sediments within the fluid  
45 combines the diffusion of the material sediments and the advection  
46 induced by the sediment settlement velocity. Given  $N$  the number  
47 of material present in the scene, we can compute the volume varia-  
48 tion of a sediment  $s_k$  of a material  $k \in [0, N]$  as the combination  
49 of the diffusive part (eq. (19)) and the sediment settlement velocity  
50 denoted  $v^{s_k}$ :  
51

$$52 \quad \frac{\partial V_i^{s_k}}{\partial t} = D^{s_k} \nabla^2 C_i^{s_k} - v_i^{s_k} \quad (20)$$

53 Where  $V^{s_k}$  is the volume of sediment  $s_k$ ,  $D^{s_k}$  is the diffusivity in  
54 water of the sediment  $s_k$ , and  $C^{s_k}$  correspond to the concentration  
55 of a sediment  $s_k$ :

$$56 \quad C_i^{s_k} = \frac{V_i^{s_k}}{V_i^f + \sum_n V_i^{s_n}} \quad (21)$$

57 In addition, porous materials may exhibit complex internal pore  
58 geometry, referred to as tortuosity. The intrinsic pore geometry  
59 causes sediments to reduce their travel speed through the material.  
60 It limits the sediments' velocity within the pore space based on  
61 the ratio of the sediment characteristic radius  $r^{s_k}$  and the material's  
62 pore characteristic radius  $r^{p_k}$ . We represent tortuosity as an expo-  
63 nent  $\tau$  which dictates how much  $r^{s_k}/r^{p_k}$  impacts sediment speed. A  
64 velocity reduction factor *filter* can be expressed as:

$$65 \quad \text{filter}_i = (1.0 - r^{s_k}/r^{p_k})^{\tau_i} \quad (22)$$

$$66 \quad \text{filter}_{(i,j)} = \min(\text{filter}_i, \text{filter}_j) \quad (23) \quad 67$$

68 Since the number of materials and sediment is finite for each

1 scene, a look-up table can be pre-computed for each couple sedi-  
 2 ment/material. Sediment diffusion (eq. (24)) is governed by a dif-  
 3 fusivity factor  $D^{sk}$  which represents how sediments would spread  
 4 in its carrier (water in our case). We consider the filter parameter of  
 5 the particle with the strongest constraint (eq. (23)) to avoid smooth-  
 6 ing artifacts.

$$7 \quad \text{Diff}V_i^{sk} = V_i^f \sum_j \text{filter}_{(i,j)} D^{sk} (C_i^{sk} - C_j^{sk}) V_j^f \nabla^2 W_{ij} \quad (24)$$

8 Sediments may settle with time due to their density being heavier  
 9 than water. Because of that, diffusion only is not enough to repre-  
 10 sent sediment transport. We need to model the influence of gravity  
 11 on those sediments. Following Stokes' law, a sediment settlement  
 12 velocity (or terminal velocity) depends on a characteristic sediment  
 13 particle radius and its relative density to its carrier (eq. (25)).

$$14 \quad \mathbf{v}_i^{sk} = \frac{2}{9} (r^{sk})^2 \frac{\rho^{sk} - \rho_0}{\mu} \mathbf{g} f(C_i^{sk}) \quad (25)$$

15 Where  $\mathbf{v}^{sk}$  denotes the settlement velocity for the sediment  $k$ ,  $r^{sk}$   
 16 the radius of a sediment  $k$  particle, and  $\rho^{sk}$  the sediment  $k$  density.  
 17 To prevent over-saturation due to advection, [WCMT07] uses the  
 18 Richardson-Zaki relation  $f(C^{sk})$  [RZ54] which guarantees that the  
 19 sediment concentration doesn't exceed its maximal level  $\text{Max}C^{sk}$ .  
 20 This relations uses a control parameter  $\kappa_{\text{concentr}} \in [4; 5.5]$ :

$$21 \quad f(C^{sk}) = \begin{cases} 1 - (C^{sk}/\text{Max}C^{sk})^{\kappa_{\text{concentr}}} & , C^{sk} < \text{Max}C^{sk} \\ 0 & , C^{sk} \geq \text{Max}C^{sk} \end{cases} \quad (26)$$

22 The terminal velocity of a spherical particle falling in a steady  
 23 fluid is given by (25). We use this formulation to express the ve-  
 24 locity of sediments in fluids both external and inside the pores of  
 25 the objects. As in Section 3.2, we propose another donor-acceptor  
 26 scheme to solve sediment advection between particles with the fol-  
 27 lowing equation:

$$28 \quad \text{Adv}V_i^{sk} = - \sum_j \begin{cases} V_j^f V_j^{sk} \text{filter}_{(i,j)} (\mathbf{v}_{ij}^{sk} \cdot \mathbf{x}_{ij}) \nabla W_{ij} & , \mathbf{v}_{ij}^{sk} \cdot \mathbf{x}_{ij} \geq 0 \\ V_i^f V_i^{sk} \text{filter}_{(i,j)} (\mathbf{v}_{ij}^{sk} \cdot \mathbf{x}_{ij}) \nabla W_{ij} & , \mathbf{v}_{ij}^{sk} \cdot \mathbf{x}_{ij} < 0 \end{cases} \quad (27)$$

29 Where  $\mathbf{v}_{ij}^{sk}$  is the sediment velocity with the lowest norm between  
 30  $\mathbf{v}_i^{sk}$  and  $\mathbf{v}_j^{sk}$  to constrain the advected volume flow.

31 Any sediment present in the absence of water will be deposited.  
 32 We explicitly control the deposition from fully-evaporated water  
 33 particles by spreading the sediment volume to surrounding non-  
 34 filled particles or spawning a new solid particle at the aforemen-  
 35 tioned fluid particle position (see Section 4.1).

### 36 3.4. Erosion

37 Erosion is an important process in weathering and has a substantial  
 38 impact on the geometry of objects. It transforms cohesive materials  
 39 into small particles by tearing them from the surface. In our simu-  
 40 lation, it means the solid volume transforms into a sediment volume  
 41 in the fluid phase. Fluid in contact with solid matter induces shear  
 42 stress  $\sigma_{ij}$  caused by the relative velocity of the fluid to the solid  
 43 surface. Since the interaction only happens between solid and fluid  
 44 phases, we can ignore this process when  $i$  and  $j$  are in the same



**Figure 5:** Erosion, transport and deposition of a brittle material (brown) over an immutable material (white). Each row depicts a specific simulation step. From left to right: simulation result, sediments shown in green within the fluid, solid particles only.

phase.

$$45 \quad \sigma_{ij} = \left( \frac{\|\mathbf{v}_i - \mathbf{v}_j\|}{\|\mathbf{x}_{ij}\|} \right)^{0.5} \quad (28) \quad 46$$

47 When  $\sigma_{ij}$  becomes greater than the intrinsic stress resistance of  
 48 the material  $\sigma^k$ , erosion occurs.

49 Because erosion only occurs at the interface between solid and  
 50 fluid, it is dependent on the contact area between the two phases. In  
 51 our context, we consider this contact area as the area of the tangent  
 52 face of the enclosing cube of our particle (i.e.  $(2r)^2$  with  $r$  being the  
 53 particle radius). We propose to compute the erosion rate of the ma-  
 54 terial  $k$  for fluid particles  $i$  and solid particles  $j$  with the following  
 55 equations:

$$56 \quad \frac{\partial V_i^{sk}}{\partial t} = (2r)^2 \kappa_{\text{erosion}} \sum_j \begin{cases} \frac{V_j^k}{V_j} (\sigma_{ij} - \sigma^k), & \sigma_{ij} > \sigma^k \\ 0, & \sigma_{ij} \leq \sigma^k \end{cases} \quad (29)$$

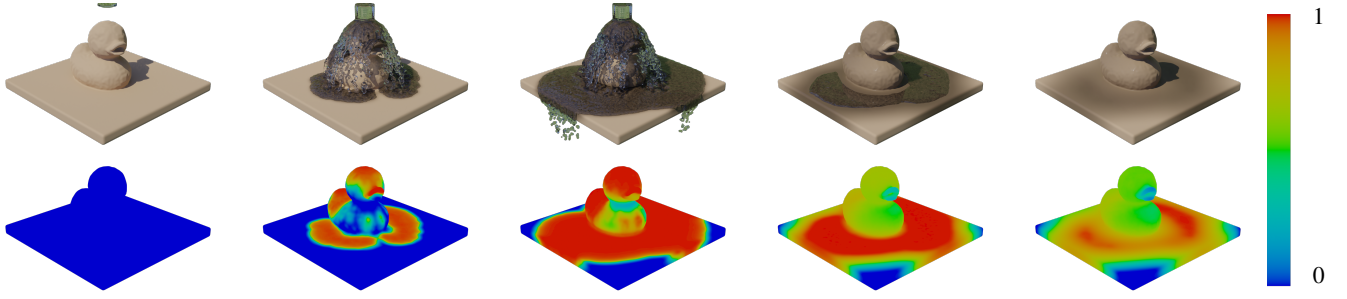
$$57 \quad \frac{\partial V_j^k}{\partial t} = -(2r)^2 \frac{V_j^k}{V_j} \kappa_{\text{erosion}} \sum_i \begin{cases} (\sigma_{ij} - \sigma^k), & \sigma_{ij} > \sigma^k \\ 0, & \sigma_{ij} \leq \sigma^k \end{cases} \quad (30) \quad 58$$

59 Where  $V^k$  is the volume of solid material  $k$  and  $\kappa_{\text{erosion}}$  is a con-  
 60 trol parameter. In practice, this formulation could result in an ex-  
 61 changed volume superior to the volume present in the solid parti-  
 62 cles. Indeed, in the case of strong shear stress or low volume parti-  
 63 cle, the computed values can get bigger than the actual volume  
 64 of the particle. In such a case, we perform an explicit exchanged  
 65 volume verification and clamp the results if necessary to guaran-  
 66 tee volume conservation. The solid volume boundary handling is  
 67 further discussed in Section 4.1.

### 68 3.5. Dissolution

69 Some granular materials have a stronger affinity to water molecules  
 70 than their surrounding ones. This affinity is called solubility, and  
 71 these materials are considered soluble (e.g., sugar, salts ...). The





**Figure 6:** Wetting and drying process of a porous material. Top: rendered view. Bottom: Heatmap of the pore saturation in water.

1 capacity of a material to be dissolved by water is correlated to its  
2 capacity to diffuse within the water.

3 Unlike erosion, dissolution does not require forces such as shear  
4 stress to occur. This process only depends on the contact area be-  
5 tween the two phases and the sediment concentration  $C^{sk}$  in the  
6 fluid phase. We use a variation of equation (24) with a concentra-  
7 tion set to  $\text{Max}C^{sk}$  for solid particles containing the material  $k$ . For  
8 a fluid particle  $i$  and solid particles  $j$ , dissolution can be written:

$$9 \quad \frac{\partial V_i^{sk}}{\partial t} = (2r)^2 \sum_j V_j^k D^{sk} (C_i^{sk} - C_j^{sk}) \nabla^2 W_{ij} \quad (31)$$

$$10 \quad \frac{\partial V_j^{sk}}{\partial t} = (2r)^2 V_j^k \sum_i D^{sk} (C_j^{sk} - C_i^{sk}) \nabla^2 W_{ij} \quad (32)$$

11  
12 As the dissolution process can be altered by various external factors  
13 (such as temperature, pressure, acidity, basicity, etc.) and depends  
14 on the material considered, we rely on this simplified model where  
15 we neglect these factors. Accounting for these factors would be a  
16 clear venue for future works.

### 17 3.6. Evaporation

18 Evaporation is a phenomenon that occurs on the surface of a liquid  
19 that progressively changes it to gas (i.e., vaporization). It is a key  
20 component of the aging process as it contributes to sediment depo-  
21 sition and crystallization. Moreover, it guides water flow in the pore  
22 space by draining water from the surface, thus causing an internal  
23 flow to reach the surface. Evaporation is mainly influenced by two  
24 factors: Temperature and Relative Humidity.

25 **Temperature diffusion** is constrained by a temperature diffusiv-  
26 ity  $\alpha$  which is defined for each material. Temperature  $T$  variations  
27 is given by Fick's law of diffusion:

$$28 \quad \frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad (33)$$

29 For each particle, we compute  $\alpha_i$  as a weighted average of its  
30 composing materials intrinsic heat diffusivity. The heat diffusivity  
31 of fluid particles is constant and set to water heat diffusivity (e.g.  
32  $\alpha_i \approx 0.143e-6 \text{ m}^2 \cdot \text{s}^{-1}$ ). We can compute the temperature diffusion  
33 using the SPH formalism:

$$34 \quad \frac{\partial T_i}{\partial t} = - \sum_j \min(\alpha_i, \alpha_j) (T_i - T_j) V_j \nabla^2 W_{ij} \quad (34)$$

35 **Relative humidity** is the proportion of the amount of water va-  
36 por in the air and the water vapor the air would contain at a spe-  
37 cific temperature to balance fluid surface evaporation. This ratio  
38 can be interpreted as the propensity of the air to capture molecules  
39 from a fluid surface. The relative humidity  $H$  is defined as the ratio  
40 of partial water vapor pressure  $p^w$  and the equilibrium water vapor  
41 pressure  $p^{*w}$ .

42 In our case,  $H$  is set by the user as the input scene meteorological  
43 condition. In order to estimate the equilibrium water vapor pressure  
44  $p^{*w}$  (eq. (35)), we use the Buck equation [Buc81] which exhibits  
45 the best accuracy between 0 and 100 degrees celsius. Most natural  
46 phenomena involving material transport matches this range.

$$47 \quad p^{*w}(T) = 6.1121 \cdot e^{(18.678 - \frac{T}{234.3}) \cdot \frac{T}{257.14+T}} \quad (35)$$

48 Since we want to obtain the partial pressure of water vapor in the  
49 air  $p^w$ , using the known relative humidity  $H_{\text{air}}$  and temperature of  
50 the air  $T_{\text{air}}$ , we can compute:

$$51 \quad p_{\text{air}}^w = H p^{*w}(T_{\text{air}}) \quad (36)$$

52 In our case, since we want to know the evaporation rate on our  
53 surface, we consider its partial water vapor pressure as its equilib-  
54 rium state for a given temperature. The water vapor pressure at a  
55 surface particle  $i$  is then given by:

$$56 \quad p_i^w = p^{*w}(T_i) \quad (37)$$

57 Pressure gradient is given by the difference between  $p_{\text{air}}^w$  and  $p_i^w$ .  
58 Taking into account the contact area between a particle and the air  
59 (see Section 3.4) and a control factor  $\kappa_{\text{evap}}$  (set to  $10^{-3}$  in shown  
60 examples), we compute the evaporated or condensed amount of wa-  
61 ter as:

$$62 \quad \frac{\partial V_i^f}{\partial t} = \kappa_{\text{evap}} (2r)^2 (p_i^w - p_{\text{air}}^w) \quad (38)$$

### 63 3.7. Sediment Deposition

64 We have seen how external water moves around the scene, how it  
65 interacts with porous mediums, and how it gets transported through  
66 the pore space. In addition, we have seen how sediments can form  
67 by being ripped off the surface of the solid or dissolved in the fluid  
68 and how the fluid transports those sediments. To finalize our sed-  
69 iment transport model, we need to account for the phase transi-  
70 tion of the sediments from fluid-carried to solid. In this section, we



1 study volume transfer from the fluid phase to the solid phase from  
2 a physical perspective. Stable solid particle insertion and volume  
3 evolution of the surface are addressed in Section 4.1.

4 The deposition is the result of particles settling on a solid sur-  
5 face. When sediments are denser than water or when concentration  
6 is above water capacity, deposition will occur. This process is re-  
7 sponsible for the transformation of sediment into solid matter.

8 As previously studied in Section 3.3, sediments settle in a fluid  
9 following equation (27). We modify this formulation for surface  
10 interaction between a fluid particle  $i$  and a surface solid particle  $j$ :

$$11 \quad \frac{\partial V_j^k}{\partial t} = (2r)^2 \sum_i \kappa_{\text{depos}} V_i^{S_k} (\mathbf{v}_{ij}^{S_k} \cdot \hat{\mathbf{x}}_{ij}) \nabla W_{ij} \quad (39)$$

12 Where  $\kappa_{\text{depos}}$  is a control parameter affecting the amount of de-  
13 position. In addition, when a fluid particle become overly concen-  
14 trated ( $C_i^{S_k} > \text{Max}C^{S_k}$ ) due to volume loss (e.g. evaporation and  
15 penetration in porous medium), sediments must be deposited on a  
16 nearby existing surface. In this case, we transfer the excess sedi-  
17 ment volume in the fluid particle to nearby surface solid particles.

#### 18 4. Implementation Details

19 In the simulation, spawning and deleting particles is a delicate pro-  
20 cess that must be carefully implemented to ensure stability. Due to  
21 the multiple phenomena our method handles, particles must appear  
22 and disappear to best represent the weathering scene. In our simu-  
23 lations, particles can only appear and disappear near the phases  
24 boundary. To enforce stability, we must ensure the boundary does  
25 not show abrupt changes over time. In this section, we describe  
26 how to handle volume variation at the boundary and how to handle  
27 outflow from a porous material.

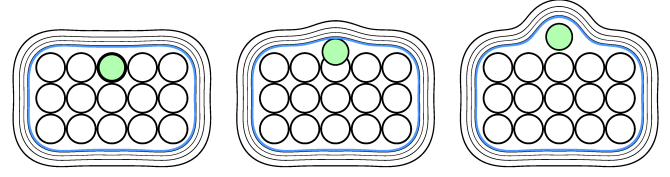
#### 28 4.1. Solid Volume Variation

29 In weathering, multiple important phenomena are related to inter-  
30 actions between different phases. A key aspect of our method is  
31 the handling of boundaries and their evolution over time. Due to  
32 deposition, dissolution, and erosion, material volumes can switch  
33 from one phase to another. When this happens, it creates a volume  
34 variation in the solid phase. We thus have to take into account the  
35 boundary modification accordingly.

36 If we only consider the solid volume scalar field for each particle  
37 during the external flow process, fluid particles could slip through  
38 solids to compensate for the volume loss of the solid particles. To  
39 ensure the iso-surface remains continuous, we adapted the bound-  
40 ary model defined by Akinci et al. [AIA\*12] which overestimates  
41 the density of particles at the boundary of the solid. In our case, we  
42 account for the solid volume variation at boundary as:

$$43 \quad \text{BoundaryVolume}(i) = \frac{V_i}{\sum_j V_j W_{ij}} \quad (40)$$

45 Weathering effects such as dissolution and erosion will remove  
46 matter from the material, whereas deposition will add matter onto  
47 the surface. These effects hence compete against each other. If  
48 managed sequentially, the result of those phenomenons would be



**Figure 7:** When solid sediment are deposited on another surface a new particle must be created (shown in green) to account for the volume change. As its volume ratio (eq. (40)) increases through time (from left to right: 0.0, 0.5, 1.0), the novel particle is gradually displaced to its final grid position.

order-dependent and would require multiple neighborhood recom- 49  
putation. On the other hand, performing all operations at once be- 50  
fore applying them to the simulation allows us to break the order- 51  
dependency and reduce the overall cost of a simulation step. Up to 52  
this point, we know the amount of matter variation at the boundary, 53  
and we need to reflect it on the solid boundary. 54

In practice, we chose to organize solid materials using a regular 55  
grid to ensure solid particles are evenly spaced within the materi- 56  
al, preventing discontinuities. In addition, this regular grid facil- 57  
itates the detection of boundary solid particles. For each grid cell, 58  
we associate at most a single solid particle. The grid cell position 59  
represents the particle position when it reaches the maximum parti- 60  
cle volume (restricted by the kernel radius). The particle position 61  
 $\mathbf{x}_i$  at the boundary of the solid can be obtained by doing a linear 62  
interpolation between the associated grid cell position  $\mathbf{x}_i^{\text{grid}}$  and a 63  
target position below the surface  $\mathbf{x}_i^{\text{subsurface}}$  using its volume ratio 64  
 $V_i/V_{\text{max}}$ . This target position is given by: 65

$$66 \quad \mathbf{x}_i^{\text{subsurface}} = \mathbf{x}_i^{\text{grid}} - 2r \frac{\hat{\mathbf{N}}}{\max(|n_x|, |n_y|, |n_z|)} \quad (41)$$

67  
68 Where  $\hat{\mathbf{N}}$  is the normalized normal vector  $\mathbf{N} = (n_x, n_y, n_z)^t$  obtained  
69 by evaluating the density field gradient at  $\mathbf{x}_i$ . Then, when a parti-  
70 cle loses volume, its position moves toward the interior of the solid  
71 material. When its volume reaches zero, the particle is fully merged  
72 in the surface. Thus, simply removing the particle from the simu-  
73 lation does not introduce any discontinuities. Similarly, when matter  
74 is added to the surface, new particles are spawned at the boundary  
75 and shifted toward the object's interior. As their volume increase,  
76 the newly-created particles progressively reach their final position  
77 without creating discontinuities on the surface (as seen in Fig. 7).

#### 78 4.2. Fluid Outflow

79 As previously discussed in Section 3.2, water can travel through  
80 the pore space of a solid material. The water volume exchanged  
81 between particles is described using equations (15) and (17). Since  
82 fluid particles are considered saturated, and diffusion transfers fluid  
83 volume from saturated particles to lesser ones, diffusion will not  
84 cause outward flow.

Using equation (17), water volume is transferred from a solid 85

1 volume particle to a fluid particle  $j$  if and only if it is located toward  
 2 the advection direction ( $\rho_0 \mathbf{g} \cdot \mathbf{x}_{ij} > 0$ ) and  $V_j^f < V_{max}$ . New fluid  
 3 particles are spawned near the surface when the porous material  
 4 contains water, and there are no fluid particles near the surface.

## 5. Results

6 In this section, we explicit the process of turning the resulting  
 7 simulated data into exploitable assets for a standard renderer  
 8 workflow, as well as discuss the results shown in our paper.

10 **Rendering:** Figures shown in this paper are rendered using the fol-  
 11 lowing pipeline. For each phase (fluid and solid), we project the  
 12 density field using SPH continuum equation (see eq. (1)) on a 3D  
 13 lattice vertices. It allows us to reconstruct the surface of each phase  
 14 by using a marching cube algorithm. To represent the sediments  
 15 contained within the fluid phase, we export a concentration field  
 16 for each by sampling their volume scalar field at each voxel of a  
 17 sparse grid using OpenVDB format. Those fields will later be used  
 18 as the absorption parameters of a volume BSDF.

19 Because we chose to use a physically-based rendering (PBR)  
 20 workflow, material textures (albedo, metallic, roughness, specular)  
 21 are created for the solid surface. We create a UV-parametrization  
 22 of the surface, and for each texel of the PBR texture, we sample the  
 23 material volume scalar fields accordingly and perform a weighted  
 24 average of the material parameters. In addition, the albedo is mod-  
 25 ified to account for the presence of sediments within the object  
 26 pores. This is obtained by using the porosity scalar field and a  
 27 per-sediment absorption parameter. The wetting effect is achieved  
 28 by darkening the material and increasing its clearcoat. Alterna-  
 29 tively, approaches like [HPMG06, BDP21] can be used to render  
 30 wet porous materials. Finally, these data are fed into a standard  
 31 production rendering engine (e.g. Blender) to produce realistic im-  
 32 agery.

33 Note that this specific rendering pipeline is purely illustrative,  
 34 and some of the chosen effects are exaggerated for better readabil-  
 35 ity.

36 **Results:** Our approach can model the interaction of multiple phe-  
 37 nomena, leading to a weathered representation of a 3D scene. In  
 38 this section, we describe how different combinations of elementary  
 39 phenomena can create different effects on the scene.

40 First, In Figures 1 and 4 we demonstrate a simple example of the  
 41 capability of our framework. In this example, we simulate making  
 42 coffee as in any good morning routine. This simulation combines  
 43 three distinct elementary phenomena to recreate the wanted effect.  
 44 First, the water is poured onto the dry coffee, then, the coffee *dis-*  
 45 *solves* into the water, and finally the water *transport* the coffee sed-  
 46 iment across the filter through *porous flow* and drips into the glass.

47 Then, in figure 5, we demonstrate erosion, sediment transport,  
 48 and deposition in a simple scene where a fluid is poured on brittle  
 49 material similar to sand. In this example, the brittle material is  
 50 *eroded* and captured by the fluid as sediment and then *transported*  
 51 within the fluid. Finally, the sediments are *deposited* elsewhere in  
 52 the scene.

53 In figure 6, we show a simulation that illustrates the porous flow



**Figure 8:** Stains produced by dirty water coming out of a hole. It shows diffusion of water and sediments in the medium and deposition on the surface after evaporation.

and evaporation. This scene is composed of single highly porous material that gets "wetted" by flow spray. This simulation shows how the *porous flow* helps transport fluid across a material. Finally, the fluid *evaporates*, and the material slowly goes back to its initial state. This simulation also illustrates the importance of simulating as many elementary phenomena as possible, especially those that modify the object boundary and composition.

In figure 8, we simulate pouring saturated fluid onto a slightly porous material. In this simulation, the fluid is saturated with colored sediment. These sediments are *transported* by the water through the *porous flow*, and leave colored stains when the fluid *evaporates*.

Figure 9 is the summarization of the different effects illustrated previously. Water is poured over a volume of soil, *eroding* it as it flows and carrying sediments over two materials, one waterproof and a porous one. Leaving *deposits* on the impervious surface and *stains* on the porous wall. Finally, the saturated water *penetrates* the wall and *seeps* into the base of the wall.

Finally, in figure 10, we simulate the complex process of efflorescence formation. This process happens when salt sediments (gypsum) are deposited when fluid (groundwater) *transport*s it through a material *porous space* via capillary action. These sediments are *deposited* on the surface of the object due to the *evaporation* of their carrier fluid.

## 6. Discussion & Limitations

As shown above, our method can handle interactions between the pore space and external fluids. However, it does not account for in-

1 interactions within the pore space. For instance, when fluid travels in  
 2 the porous medium, dissolution can affect the size of internal pores.  
 3 Similarly, sediment deposition or crystallization can also affect the  
 4 internal geometry of the object and can lead to internal stress or  
 5 structure deformations (e.g., cracks caused by salt crystallization,  
 6 peeling paint layer on a wet wood surface). Considering these internal  
 7 interactions would be a promising venue for future works.

8 Since wetting plays an essential role in a wide range of phenom-  
 9 ena, it would be interesting to study the airflow and its interaction  
 10 with the porous medium. It would allow a more accurate model of  
 11 the water vapor pressure in the whole volume instead of relying  
 12 solely on the temperature at the interface. Furthermore, a refined  
 13 water vapor model could allow for a precise organic growth model  
 14 within the porous mediums. In a more general manner, chemical  
 15 interactions between fluid, sediments and solid matter could widen  
 16 the range of phenomena we can depict (e.g. rust formation, corro-  
 17 sion) and enrich our simplified dissolution model.

18 In the case of water flowing through and dripping from a materi-  
 19 al (as illustrated in Fig. 1 and Fig. 4), the fluid outflow described  
 20 in Section 4.2 requires the creation of new particles. As newly cre-  
 21 ated particles may have a low volume, the number of particles con-  
 22 sidered within the neighborhood can be large, hampering perfor-  
 23 mances in the scenes mentioned earlier.

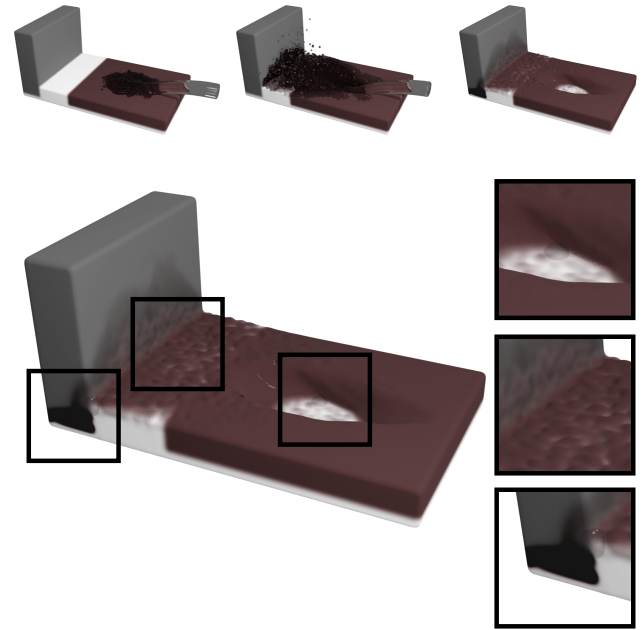
24 All results shown in this work consider solid volumes to be static.  
 25 In order to integrate moving objects, approaches relying on per-  
 26 object local grids (like [WCMT07]) could be considered. However,  
 27 our proposed solid volume handling (see Section 4.1) should be un-  
 28 suitable in the context of multiple moving objects. More specially,  
 29 objects that are close to each other must be carefully considered  
 30 when new particles spawn at their common interface and should re-  
 31 quire taking to account mechanical forces. Despite everything, our  
 32 proposed porous flow model should remain correct if we integrate  
 33 motion acceleration during advection computations.

## 34 7. Conclusion & Future Works

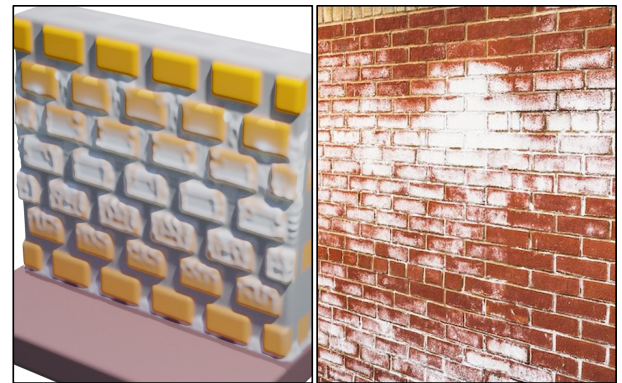
35 Our main objective is to produce the weathered representation of a  
 36 pristine scene to enrich realistic imagery. In this context, we pre-  
 37 sented a framework based on SPH to model interactions between  
 38 porous objects, fluid, and sediments.

39 This model can depict reversible phenomena like wetting and  
 40 evaporation. It can also handle alteration of the object geometry  
 41 through dissolution, deposition, and erosion and the alteration of  
 42 object appearance via deposition and sediment transport. Through  
 43 the interactions between these processes, our framework success-  
 44 fully approximates physically plausible results which can be found  
 45 in nature.

46 More interactions between materials could be accounted for in  
 47 future works by solving the chemical reactions occurring in the  
 48 scene. Furthermore, the accurate simulation of interactions within  
 49 the pore space could lead to new research in organic growth and  
 50 mechanical simulation for weathering. Finally, using the simulation  
 51 data to deduce a mesoscale spatially-varying BSDF could reduce  
 52 the gap between simulations of the aging process and the rendering  
 53 of a weathered scene.



**Figure 9:** Erosion, Transport, Deposition and Porous flow occurring in the same scenario. **Top row** shows different points of the animation: before, during and after the water jet. **Middle** exhibits the outcome of the simulation. **Insets** depicts close-ups of the illustrated effects, from top to bottom: erosion, deposits and stains, porous flow.



**Figure 10:** Efflorescence process on a brick wall. Salt is carried from the underground to the surface by ground water. It then deposits on the surface due to evaporation resulting in gypsum formation. **Top row:** Pristine wall. **Bottom row:** Weathered wall. **Left column:** Particle representation. **Right column:** Rendered result.



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