SIGGRAPH ASIA 2015 KOBE

WetBrush: GPU-based 3D Painting Simulation at the Bristle Level

Zhili Chen,[1,2] Byungmoon Kim,[2] Daichi Ito,[2] Huamin Wang[1]

[1]The Ohio State University
[2]Adobe Research

Sponsored by

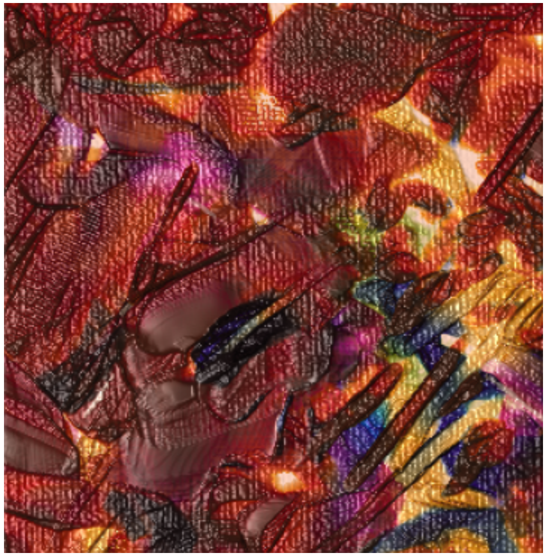
Oil Painting

- Complex physical interactions
  - Bristle-Bristle
  - Bristle-Fluid
  - Fluid-Fluid
- Simulate them!

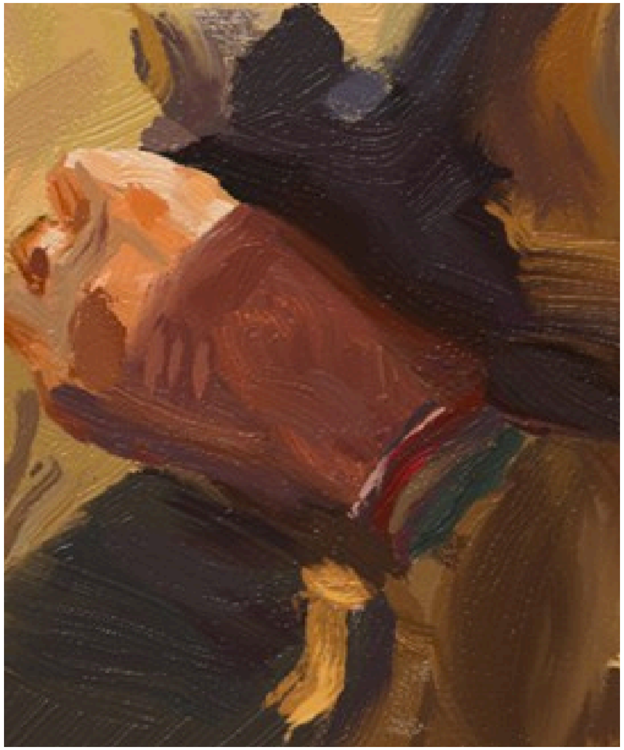
Real-world footage

Previous works

- Paint Fluid Model
  - Height field
  - 3D volumetric density grid



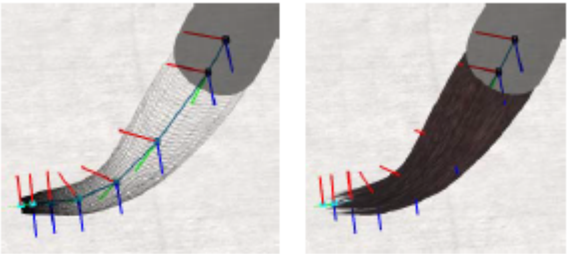
Baxter, et al. 2004



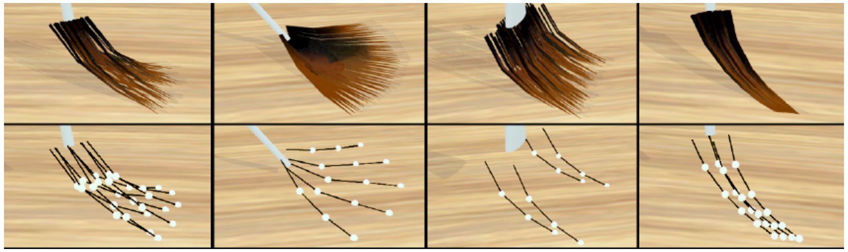
Chu, et al. 2010

Previous works

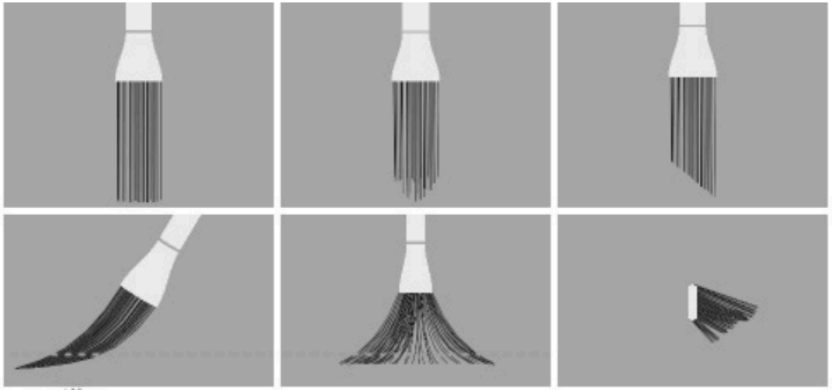
- Brush Model
  - 2D stamping
  - 2D Surface wrapped around skeleton
  - 3D Brush projected onto 2D stamp
  - Individual Bristles



Chu et al., 2002



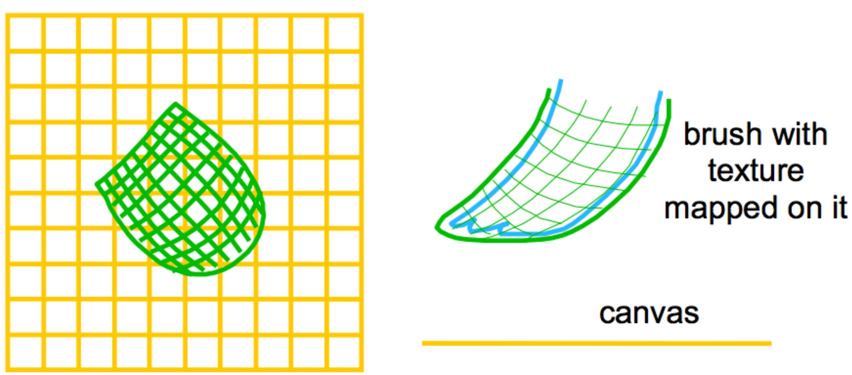
Baxter et al., 2004



DiVerdi et al., 2010

Previous works

- Brush-Paint Fluid Interaction
  - Brush-Fluid one way interaction
    - Deform when collide with canvas
    - Imprint generated using as boundary condition
  - Simple color transfer/pickup function with texture map
    - In 2D imprint space
    - Wrapped surface space



Chu, et al. 2010

What is missing?

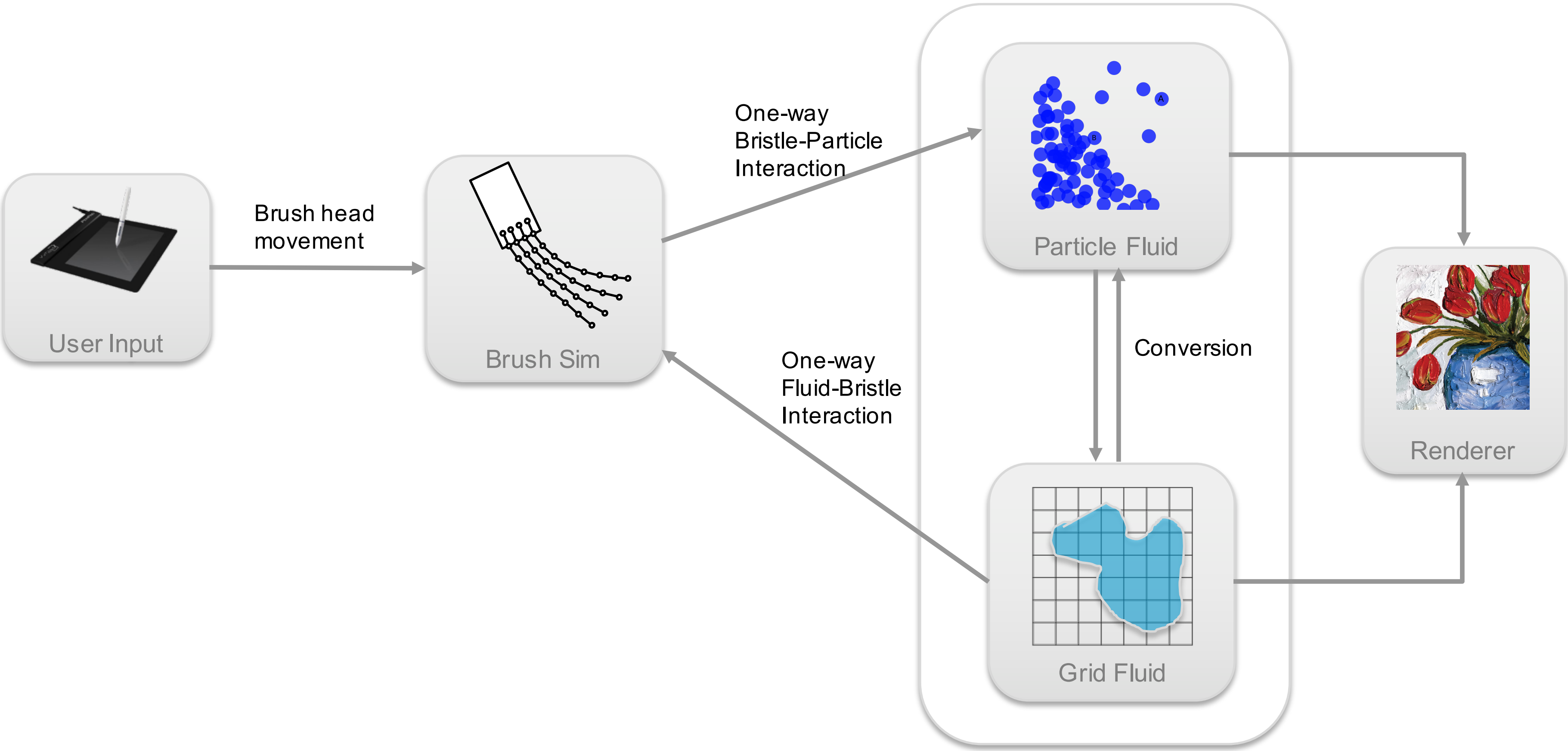
"Not feel like real while painting"

- Artists who are familiar with traditional media want
  - Correct brush deformation under force
  - Brush that carries paint liquid for intuitive paint deposition
  - Natural color mixing
  - Fine details, not overly-smooth color
  - Stroke variations and happy accident

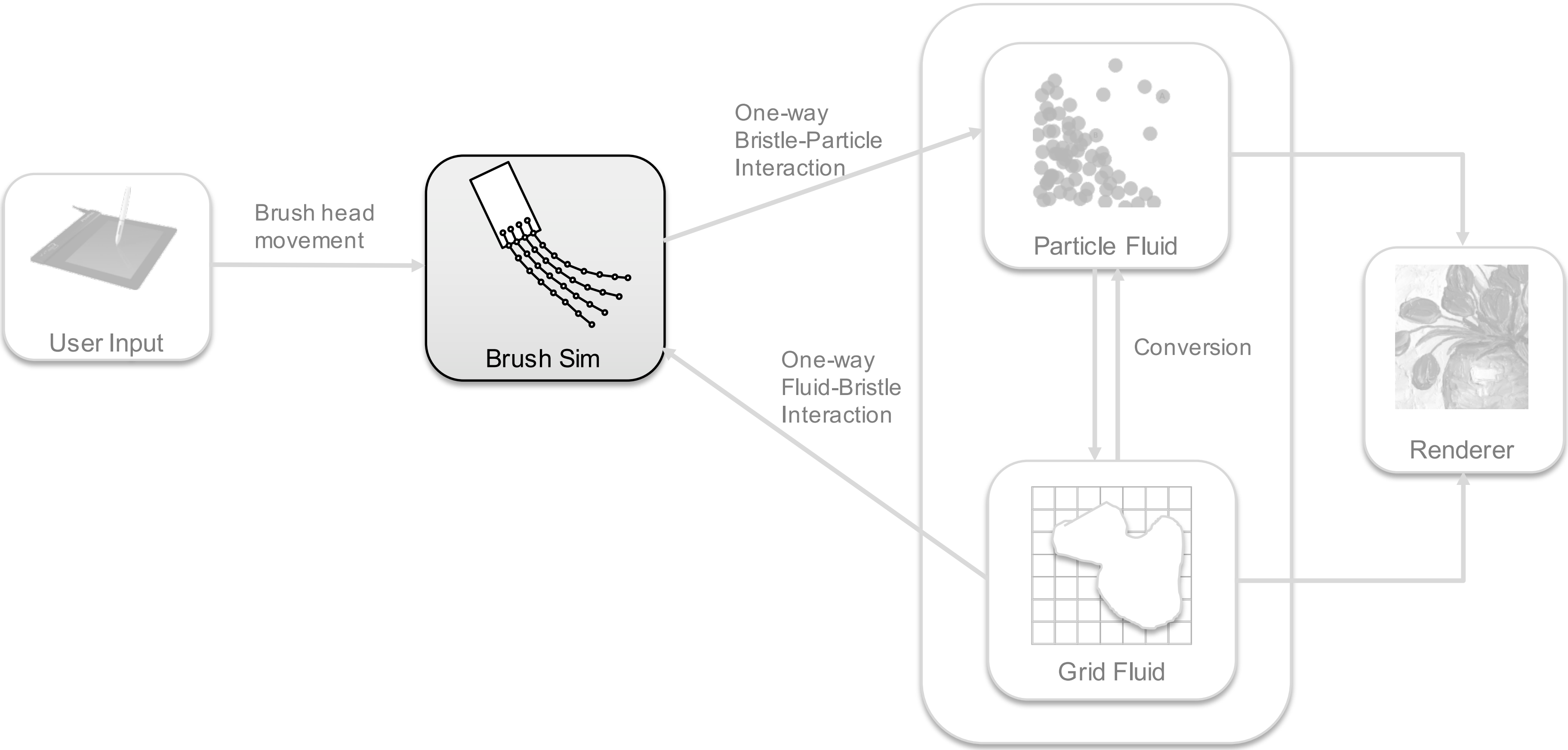
Motivation

- Oil Painting observed from molecule level
  - Brush carry paint
    - Adhesion between bristle molecule and fluid molecule
    - Cohesion among fluid molecule
  - Color mixing
    - Fluid molecules carrying different pigments gather and show mixed color

System Overview



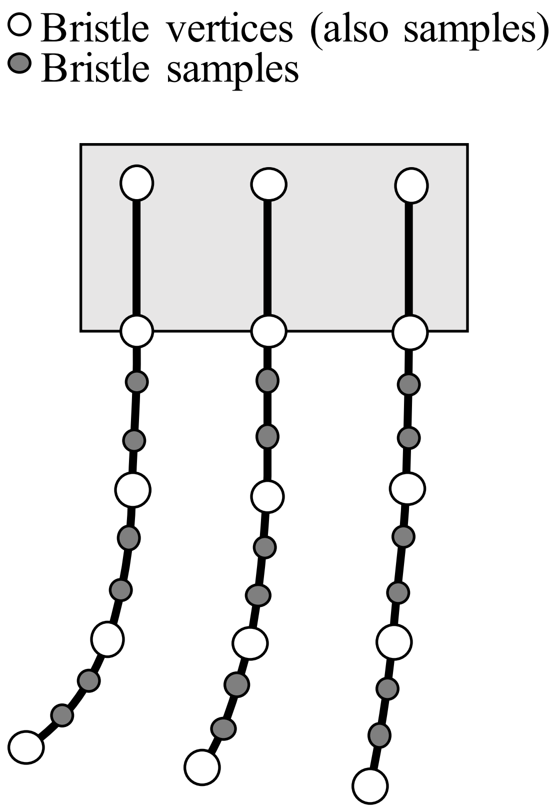
Brush



User Input
Brush head
movement
Brush Sim
One-way
Bristle-Particle
Interaction
One-way
Fluid-Bristle
Interaction
Particle Fluid
Conversion
Grid Fluid
Renderer

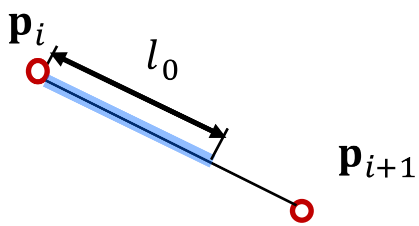
Brush Model

- Model individual bristles
  - Bristle Vertices
    - For brush dynamics
    - ~10 per bristle
  - Bristle Samples
    - For paint interaction
    - B-spline curve
    - Denser sample near tip
    - ~50 per bristle
  - 50-200 bristles

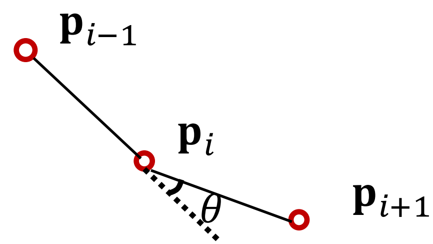


Brush Dynamics

- Position-based Dynamics

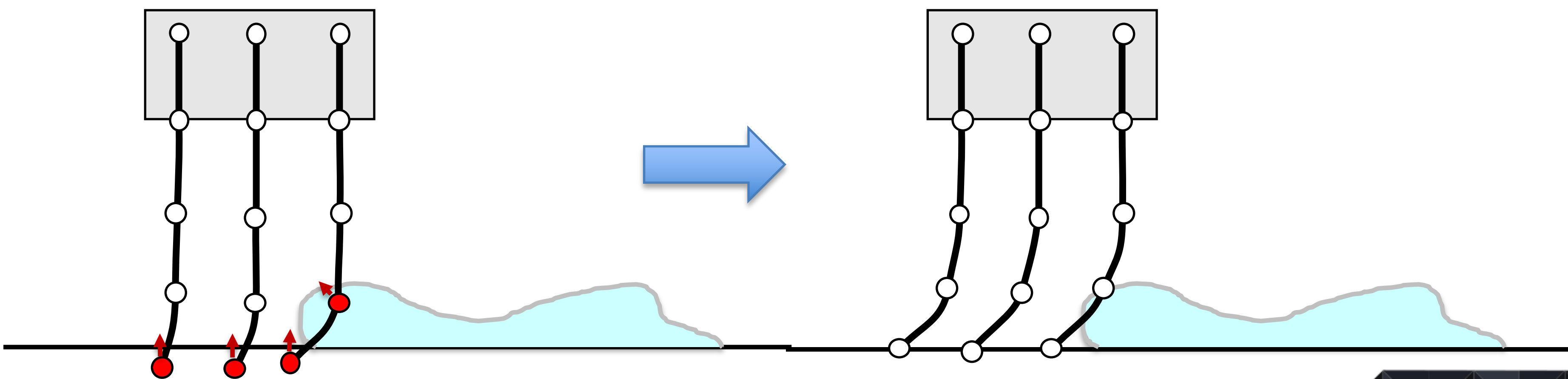


In-extensiblity



Bending

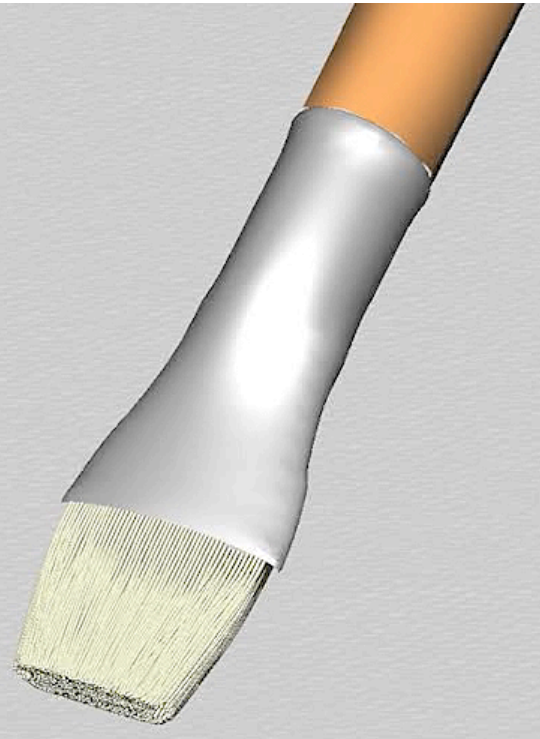
- Collide with canvas/dry paint surface



Brush Dynamics

- Bristle-Bristle Contact
    - Essential for correct brush shape under deformation
- Precise line-line collision processing?
    - Too expensive for real-time
- Particle based collision
    - SPH style repulsion
        - Avoid over-compression
    - Laplacian velocity filtering for inter-bristle friction

Brush

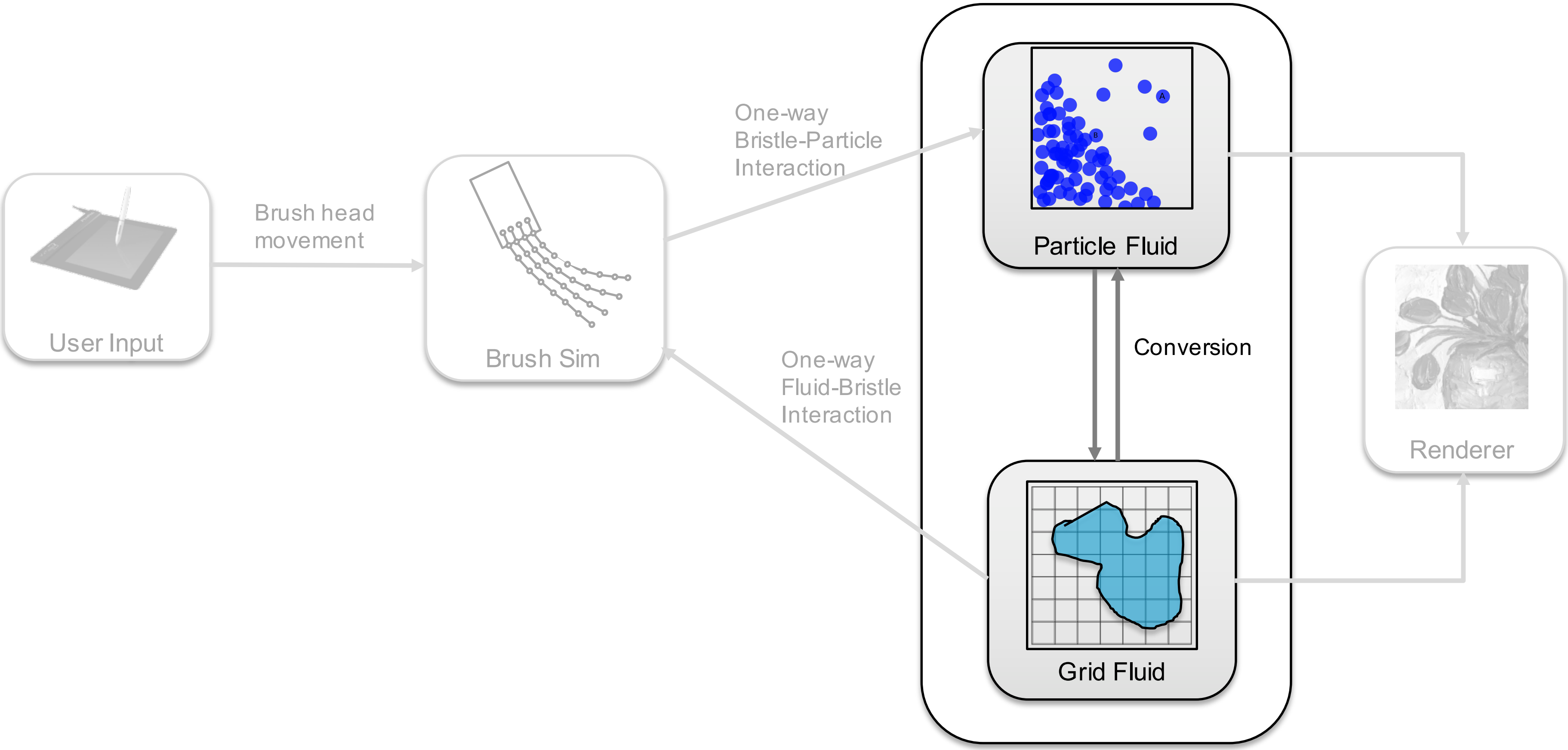


- Correct brush shape even under extreme deformation
- Stroke variations achieved from contacts between individual bristles

Brush

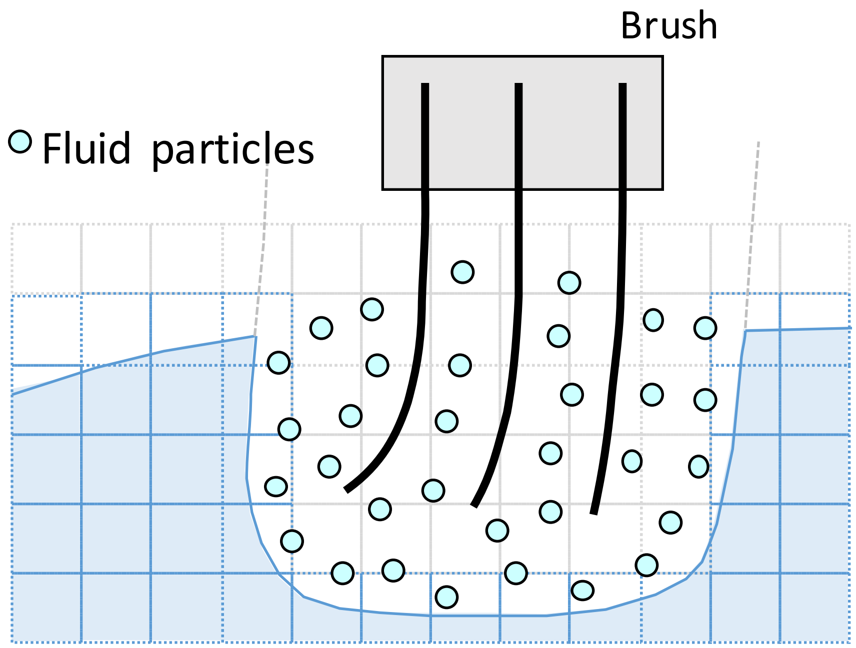
- Allow creative use of brush just like one could with real brush

Fluid Simulation



Hybrid Fluid Representation

- Adaptive Hybrid Fluid Representation based on
  - Distance to brush
  - Velocity



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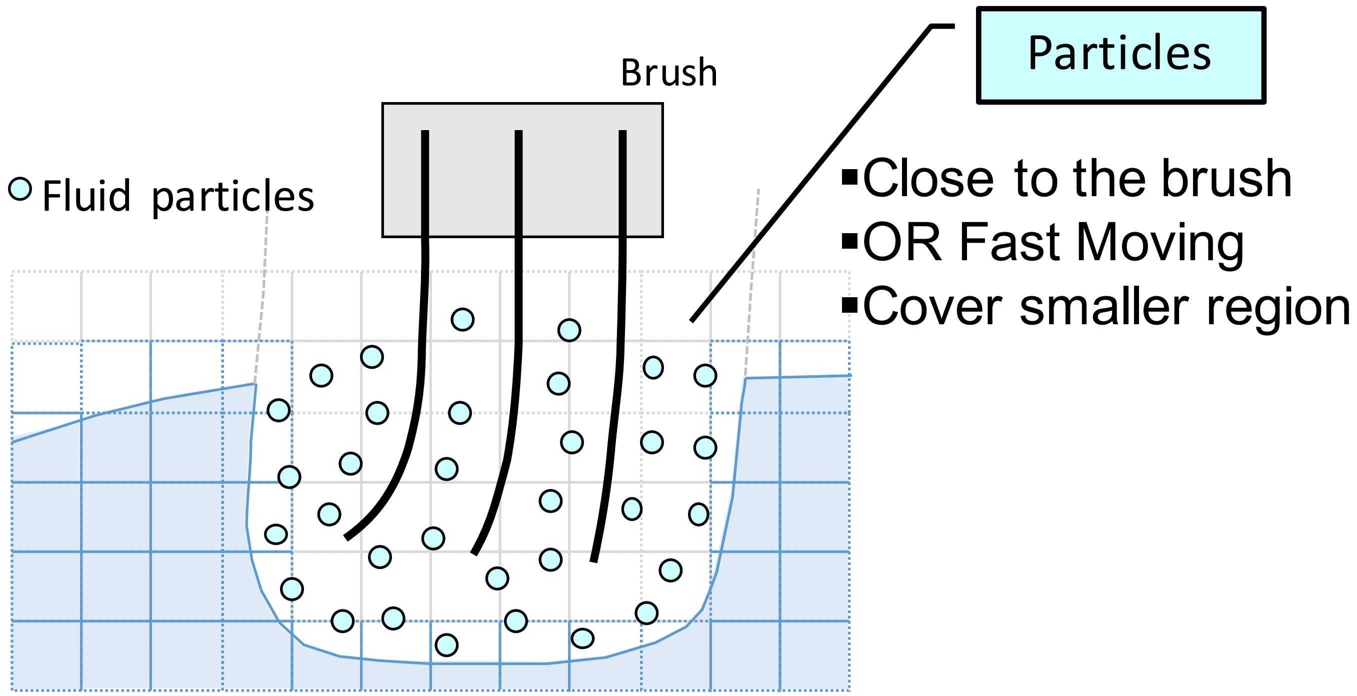

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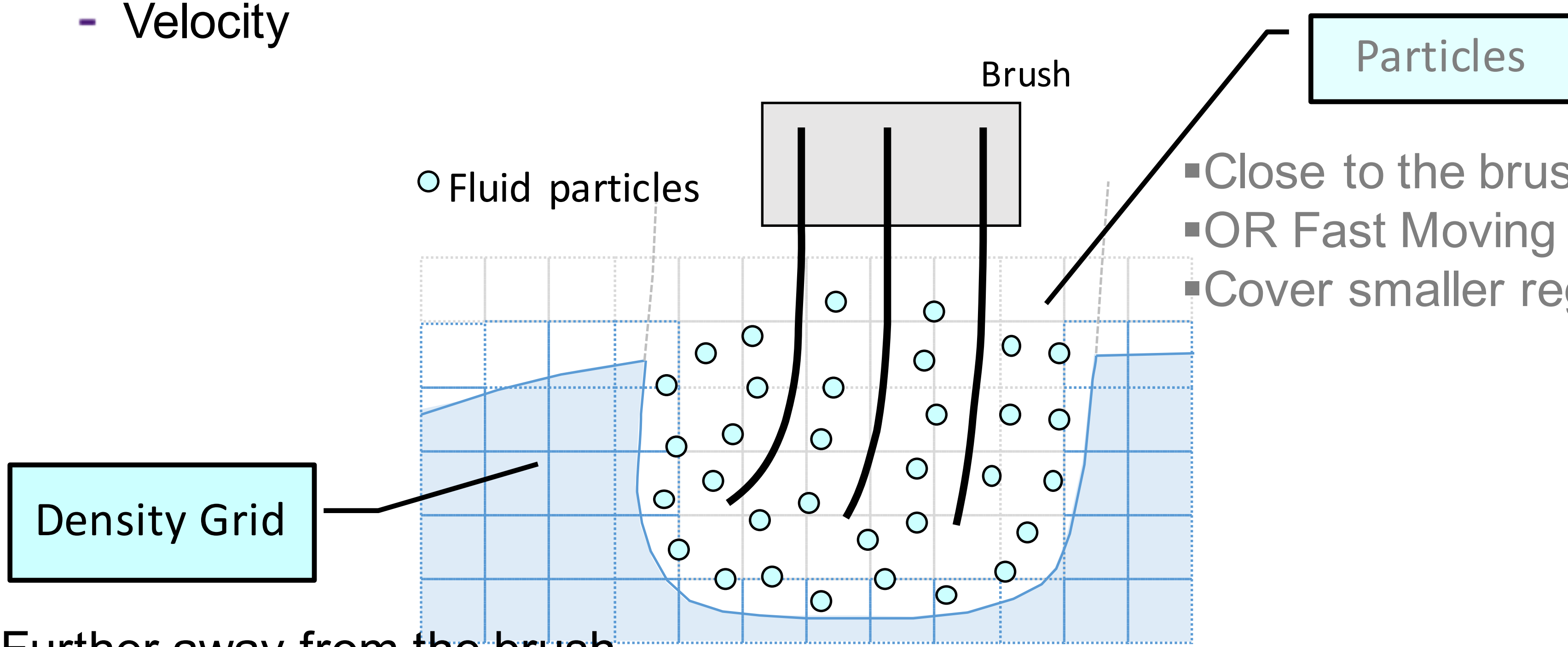


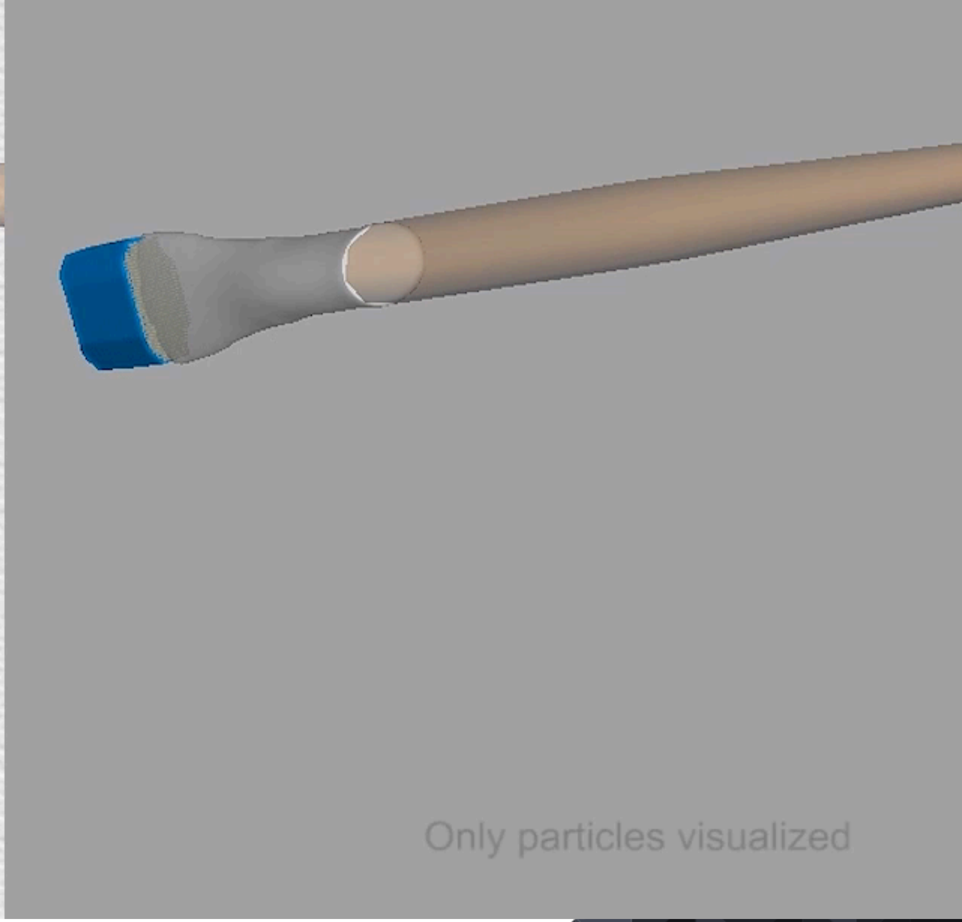
- Close to the brush
- OR Fast Moving
- Cover smaller region

- Further away from the brush
- AND Slow moving
- Cover larger region

Hybrid Fluid

Grid & Particles Visualized

Only Particles Visualized

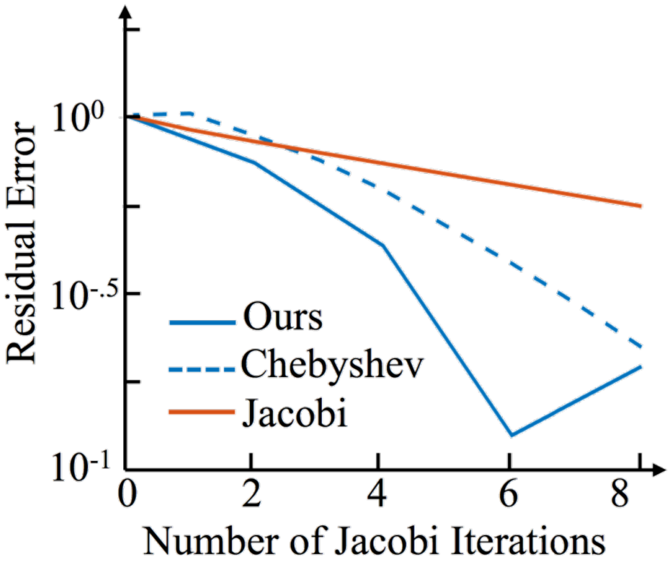


Grid Fluid

- Grid (Density, velocity, pigment, dryness, oil ratio)
  - Moving sim window (256X256X32) within full canvas grid (4096X4096X32)
  - Semi-Lagrangian Advection
  - Fast Fixed-Point Jacobi Method for solving pressure projection
    - Only 2-6 Jacobi iterations needed for acceptable error level
    - Suitable for real-time applications
    - Grid used only for slow moving region

Algorithm 1 `Fixed_Point_Pressure_Projection`($\mathbf{u}$, P)

for $l = 1, \ldots, L$ **do**
  $P = \alpha P$;
  $D = \nabla \cdot \mathbf{u}$;
  $P =$ `One_Jacobi_Iteration`(P, D);
  $P =$ `One_Jacobi_Iteration`(P, D);
  $\mathbf{u} \leftarrow \mathbf{u} - \nabla P$;
return $\mathbf{u}$;

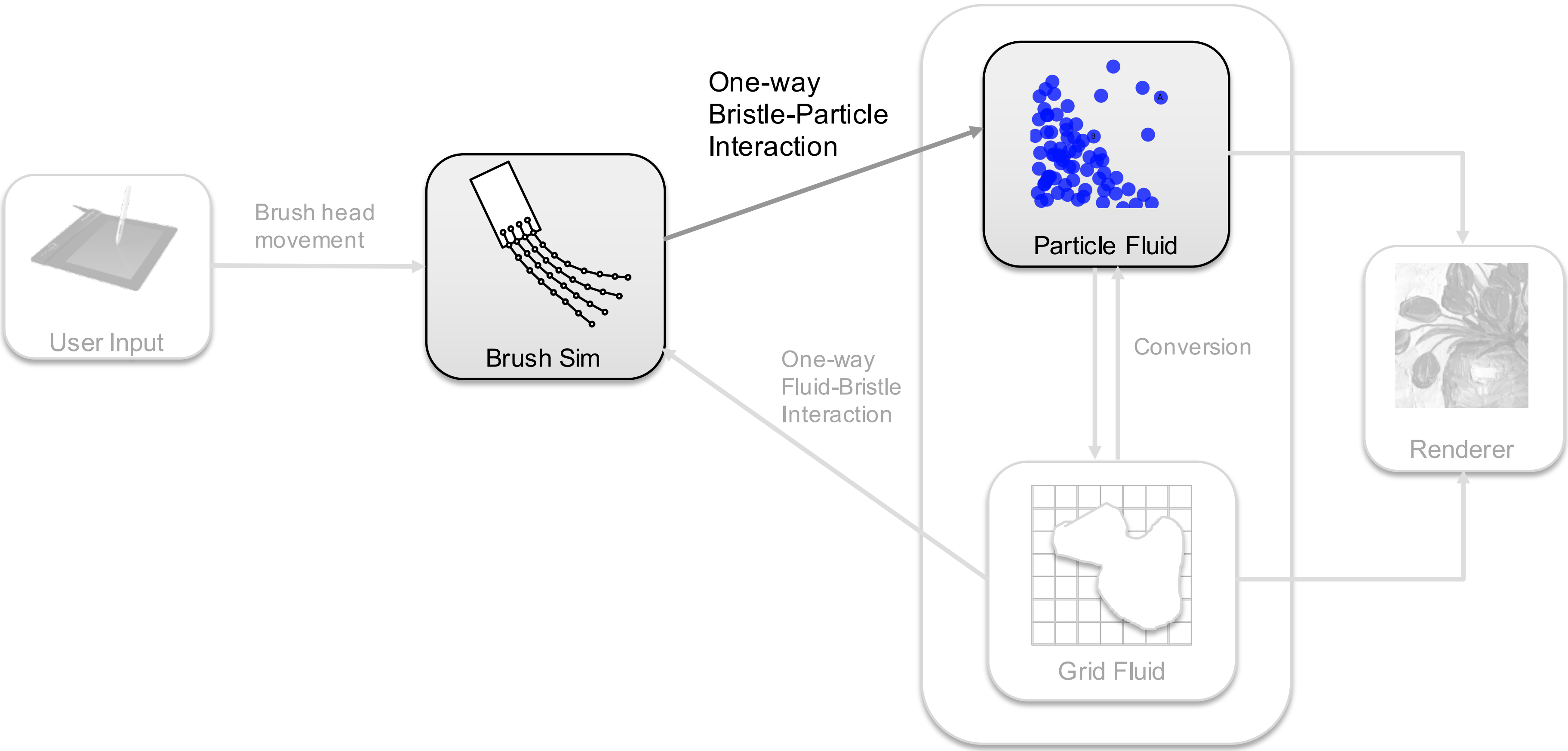


See paper for details

Particle Fluid

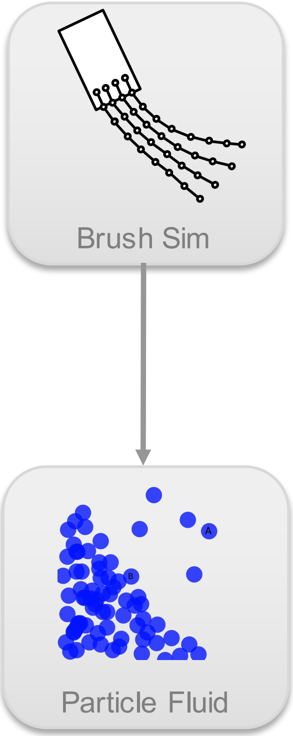
- Particles (velocity, pigment, oil ratio)
  - Interact with bristle sample points
  - Borrow Grid fluid velocity field for incompressiblity in FLIP/PIC way
  - Allow small amount of volume loss
- vs. SPH / Position-Based Fluid
  - Less noisy (good for viscous fluid appearance)
  - Faster (+ pressure projection already needed in grid)

Particle-Bristle Interaction



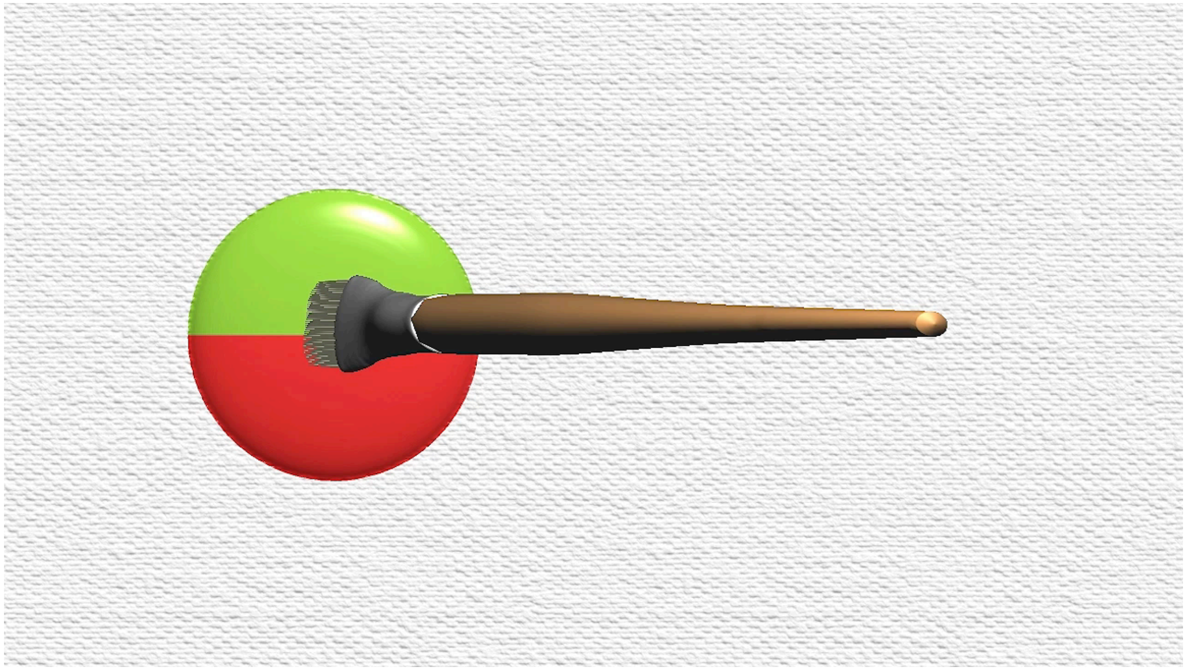
Particle-Bristle Interaction

- Brush pushes fluid
  - Bristle sample points as boundary condition
  - Particles get SPH repulse from bristles
- Brush carries fluid
  - Directly compute adhesion force?
    - Adhesion is strong
    - Unstable stiff system with large timestep
    - Small timestep/substepping => non-real-time



Bristle-Particle Adhesion

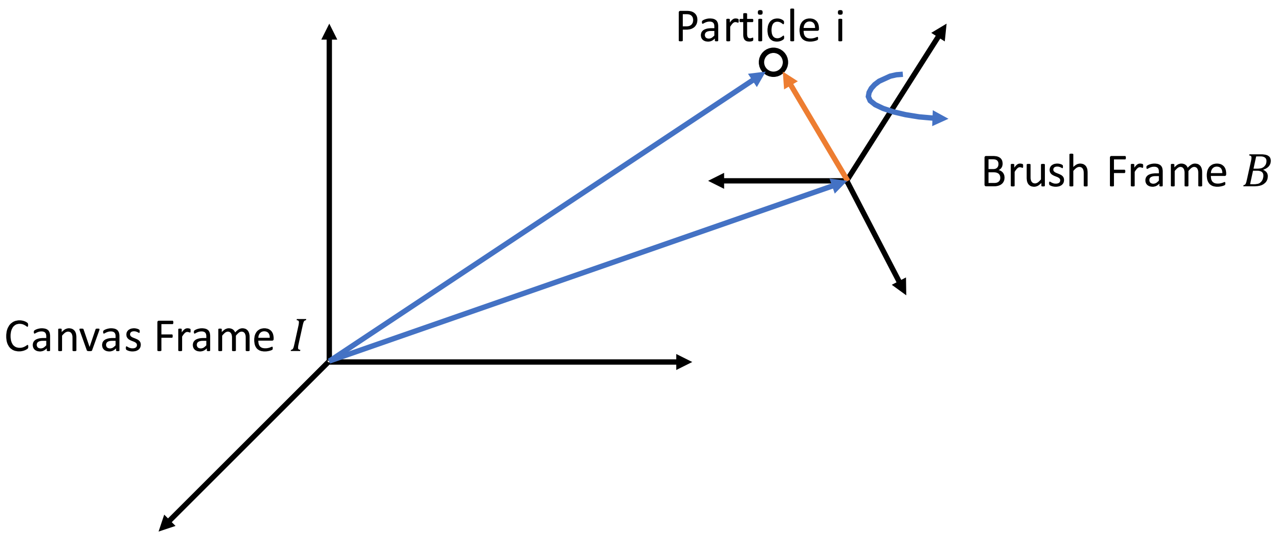
- Explicit adhesion force
  - $\boldsymbol{f}_a = -kf(\boldsymbol{d}_b)$
  - Particles fail to follow fast moving brush



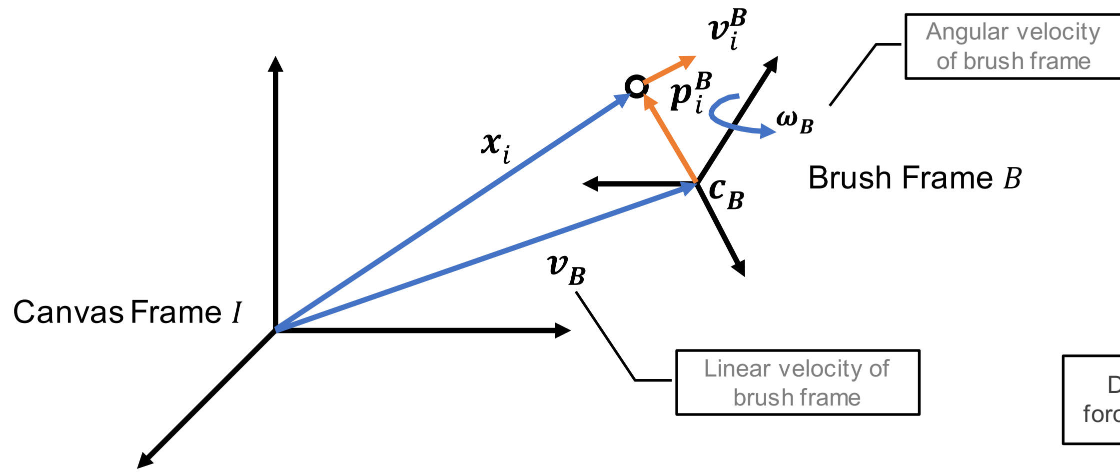
Bristle-Particle Adhesion

Brush and fluid particles carried

- Has little relative movement
- Adhesive force counteract inertial acceleration
- Better modelled in brush non-inertial frame



Stable Position-Based Adhesion



Direct adhesion force in brush frame

Acceleration in brush frame

$$a_i^B = R_B\ a^{ext} - (\dot{v_B} + 2\omega_B \times v_i^B + \omega_B \times (\omega_B \times p_i^B) + \dot{\omega}_B \times p_i^B) - \frac{k}{m_i} \boldsymbol{d}_b^B$$

External forces in canvas frame – gravity, friction, etc.

Frame linear acceleration

Coriolis acceleration

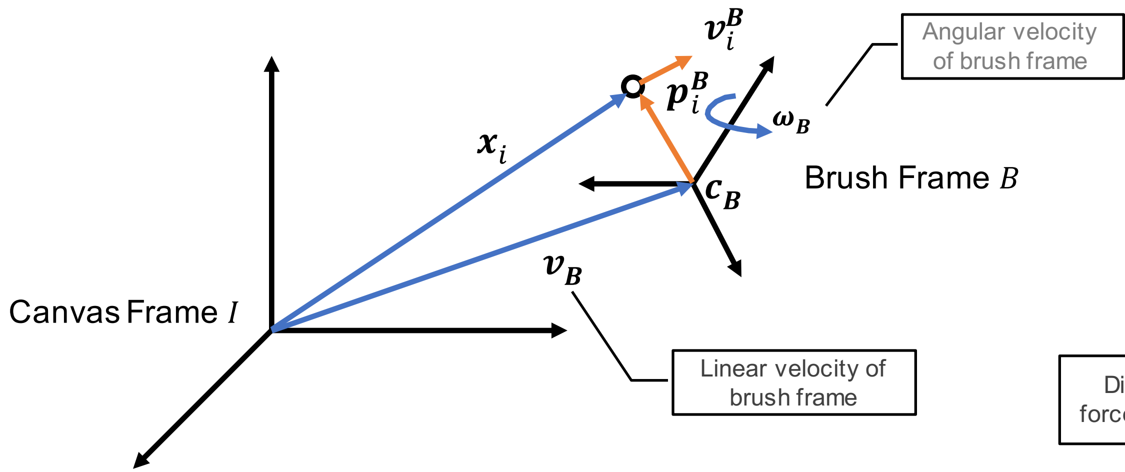
Centrifigual acceleration

Frame angular acceleration

R_B : transformation from canvas frame to brush frame

$$p_i^B = R_B(x_i - c_B)$$

Stable Position-Based Adhesion

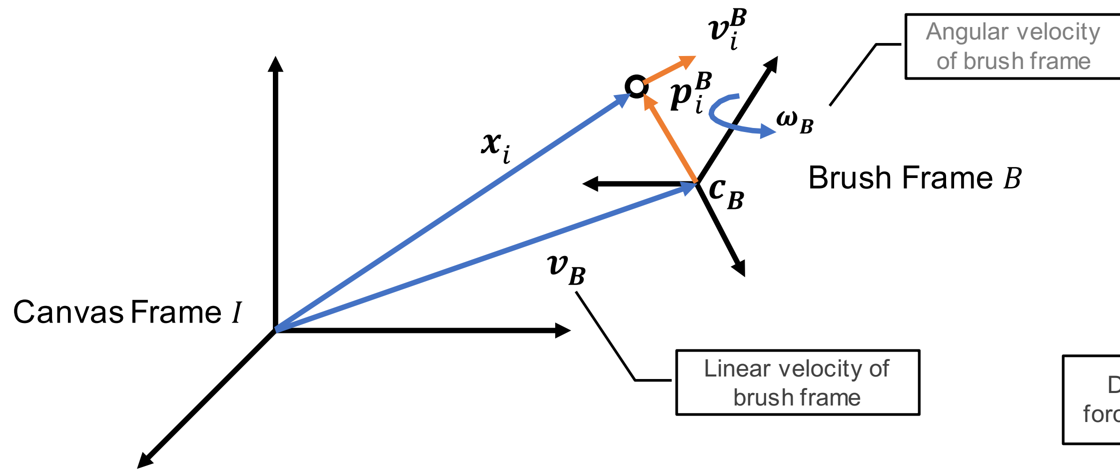


Direct adhesion force in brush frame

$$a_i^B = R_B\ a^{ext} - \left(\dot{v}_B + 2\omega_B \times v_i^B + \omega_B \times \left(\omega_B \times p_i^B\right) + \dot{\omega}_B \times p_i^B\right) - \frac{k}{m_i}\mathbf{d}_b^B$$

Inertial acceleration

Stable Position-Based Adhesion



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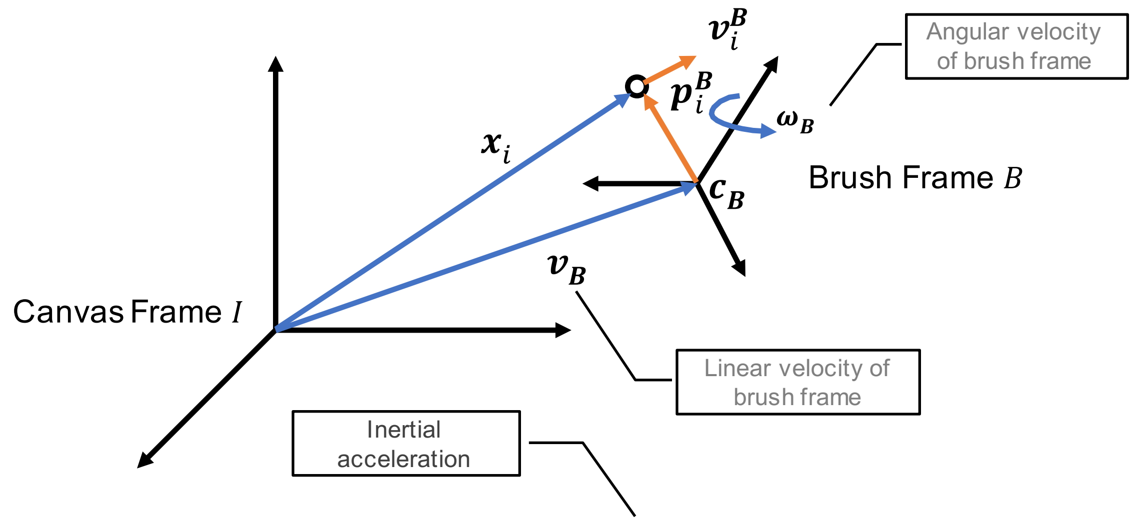
Inertial acceleration

Stable Position-Based Adhesion



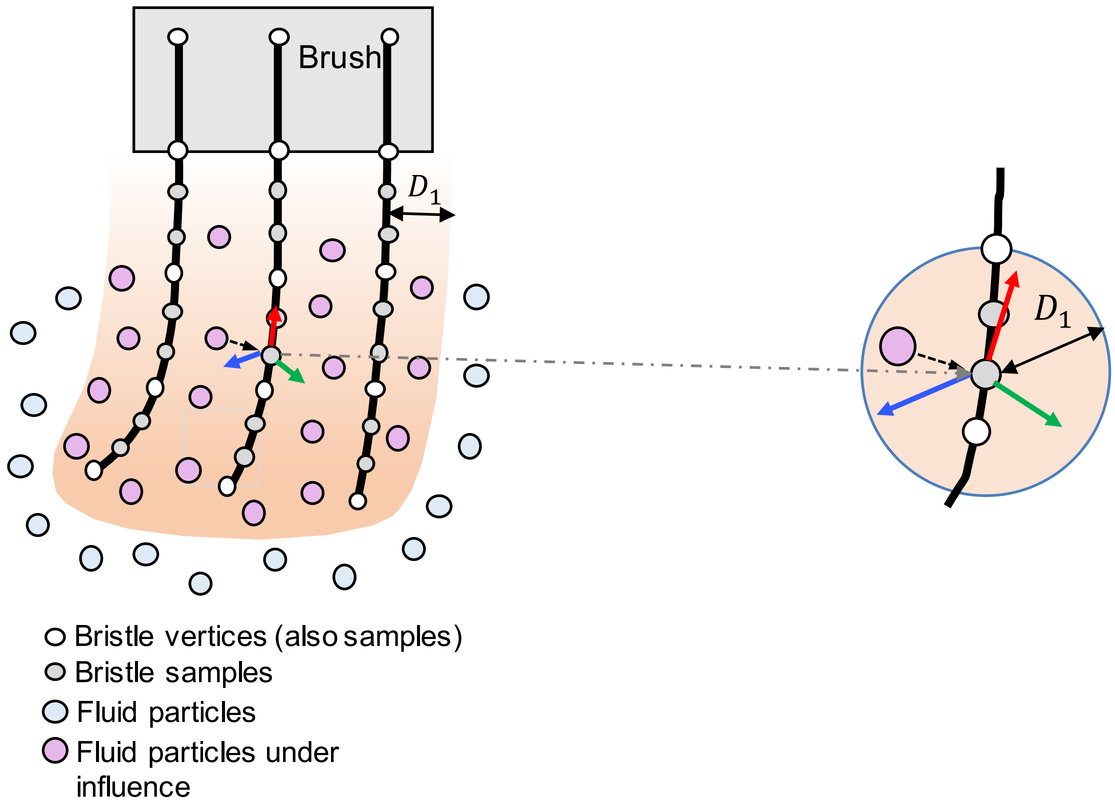
$$a_i^B = R_B\ a^{ext} \underline{- \beta(\dot{v}_B + 2\omega_B \times v_i^B + \omega_B \times (\omega_B \times p_i^B) + \dot{\omega}_B \times p_i^B)}$$

$$\beta = \beta(\boldsymbol{d}_b^B)$$

β: A function of distance to brush

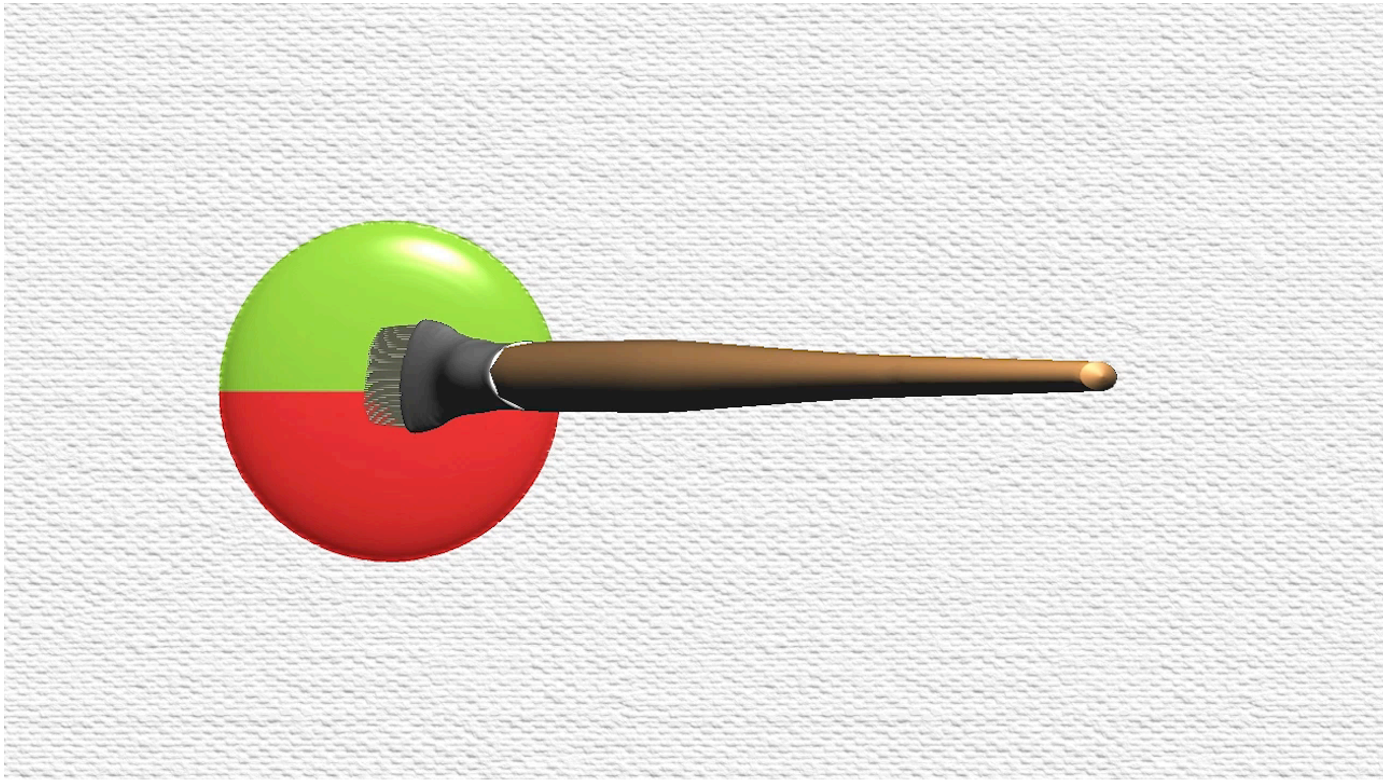
Stable Position-Based Adhesion

- Keep local non-inertial frame for every bristle sample point
- Particles assign to frame dynamically



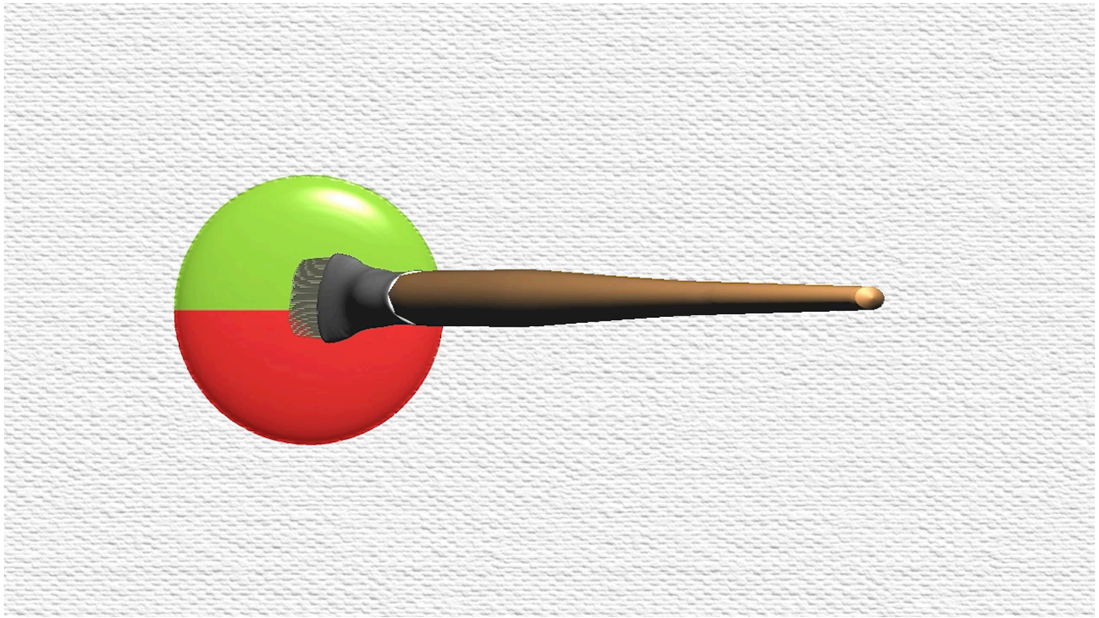
Stable Position-Based Adhesion

- Brush carries paint by stable adhesion
- Natural mass preserving deposition of paint on canvas



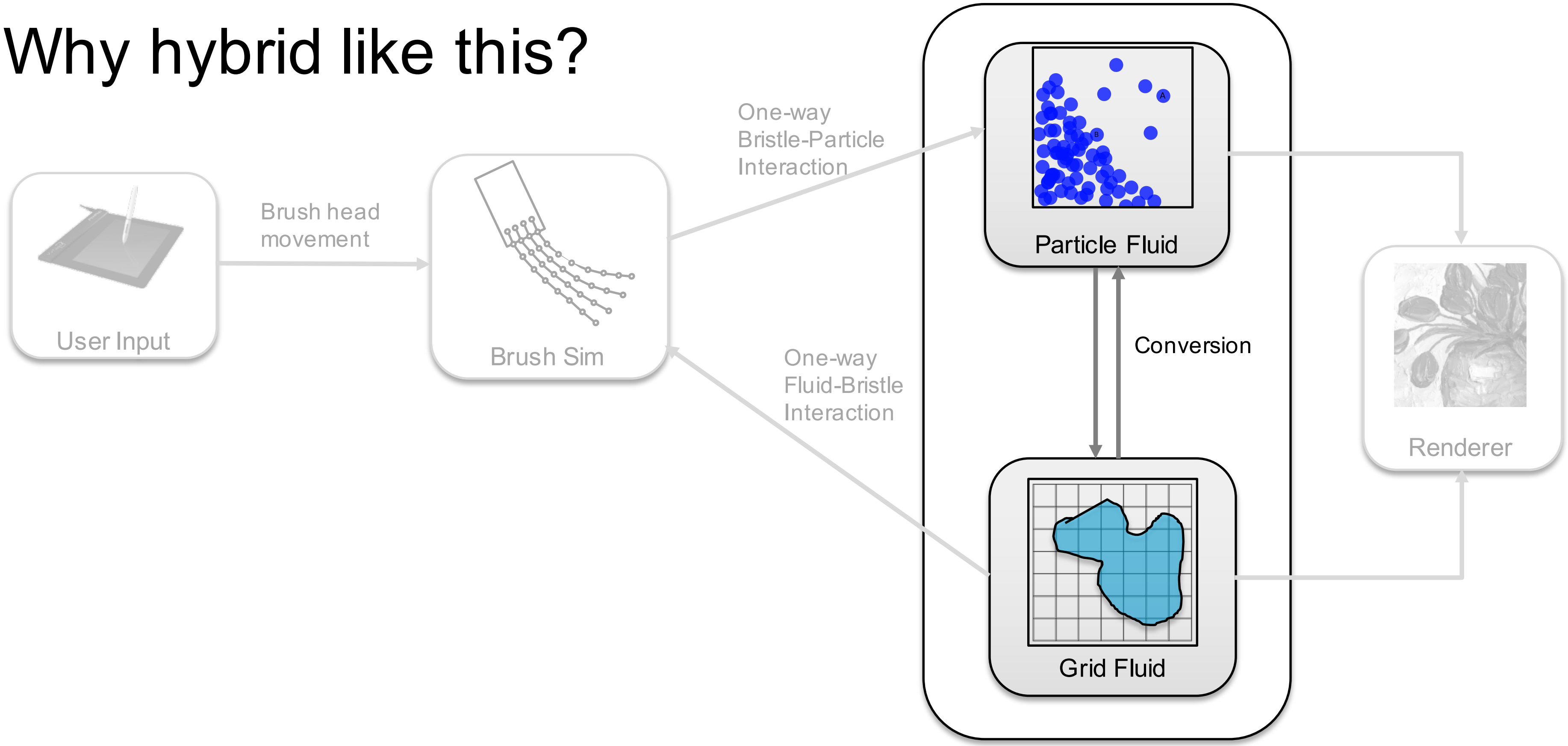
Dry Brush Load

- Very dry brush still can produce strokes
  - Particles carried with adhesion will run out
  - Keep minimum paint load on bristle samples
    - Emit paint fluid particles to produce stroke
    - Absorb paint fluid particles to modify color



Fluid Representation

Why hybrid like this?



Fluid Representation

Why hybrid like this?

- Volumetric grid vs. ~~Height field~~
  - Want to model overhanging paint
  - Full interaction with 3D brush

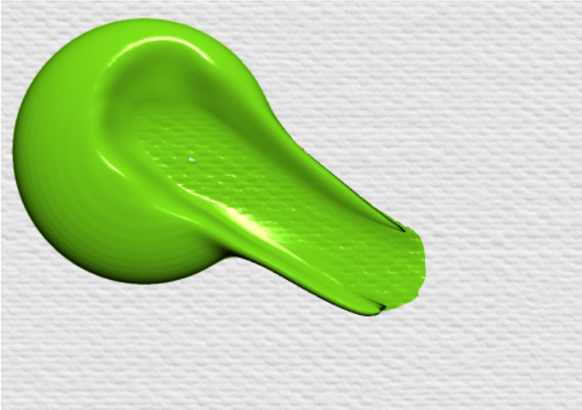
Overhang
(Photographed)

Fluid Representation

Why hybrid like this?

- Volumetric grid vs. ~~Height field~~
  - Want to model overhanging paint
  - Full interaction with 3D brush

- Particle-Grid Hybrid vs. G~~rid only~~
  - Brush carrying paint
  - Particles conserves mass so paint closer to brush does not disappear when moving fast
  - Particles tracks thin features better

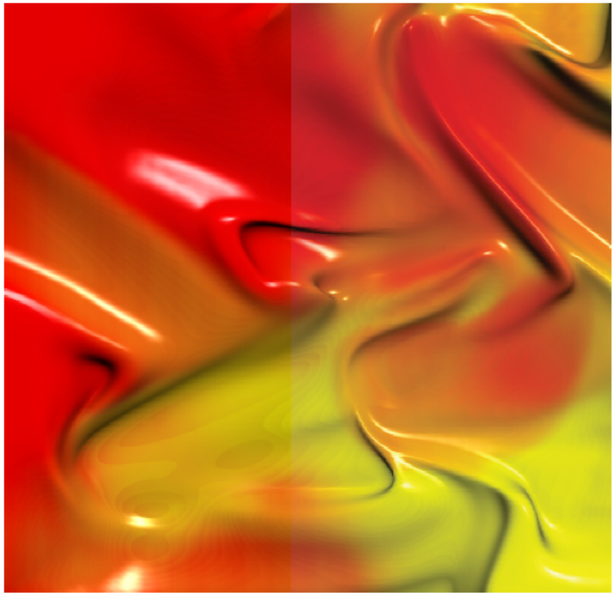


Grid Only

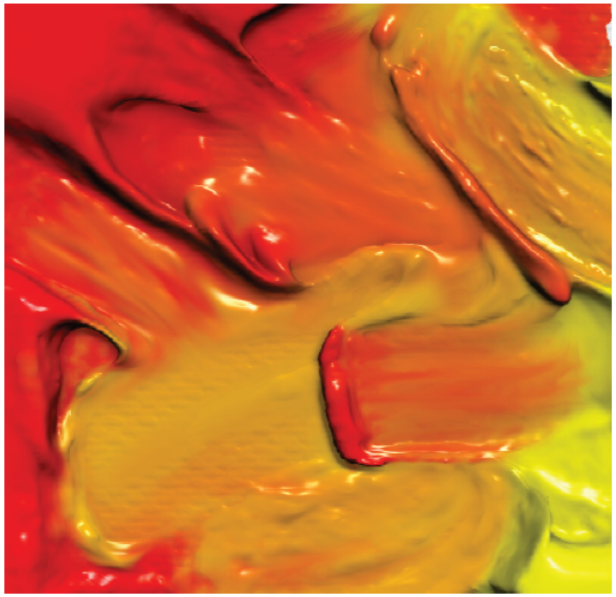
Grid+Particle

Hybrid vs. Grid-only

- Hybrid method reveals more details in
  - Surface shape
  - Color mixing



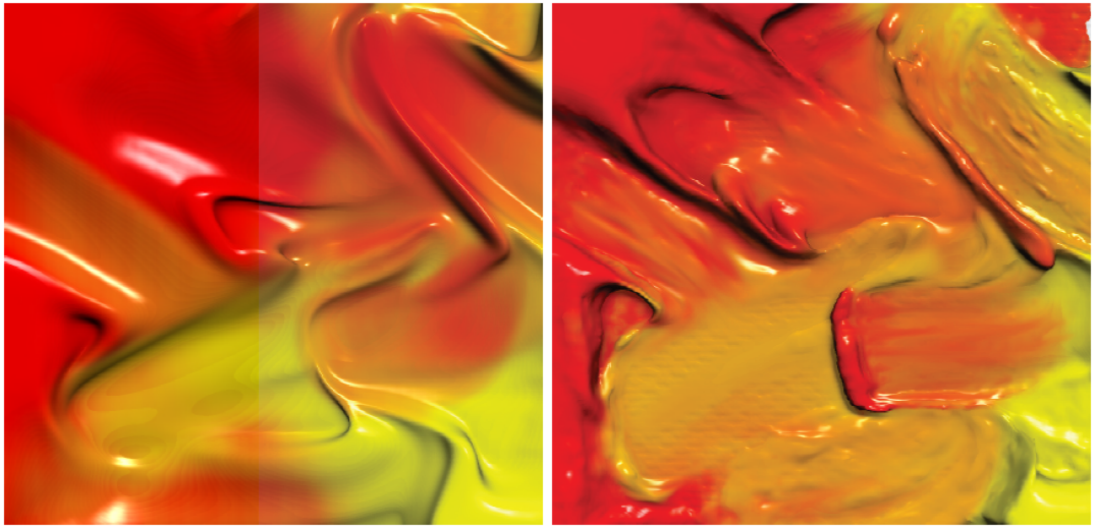
(a) Grid-based liquid



(b) Hybrid liquid

Hybrid vs. Grid-only

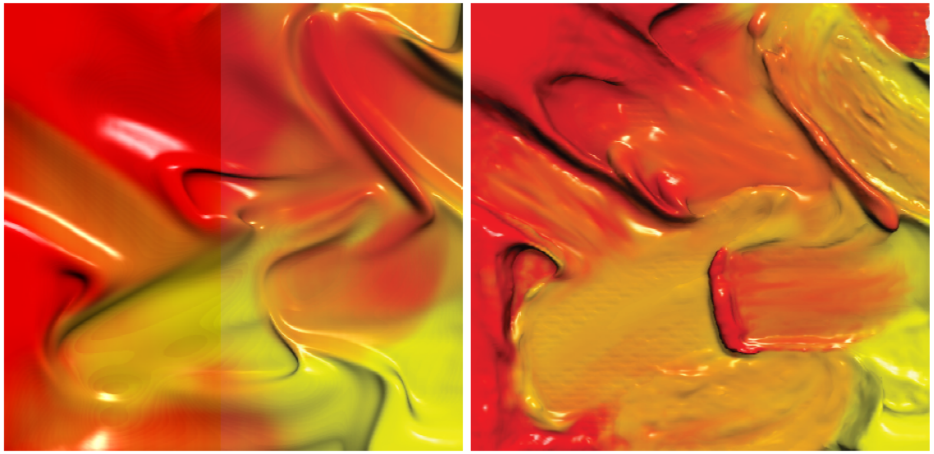
- Hybrid method reveals more details in
  - Surface shape
    - Subpixel level solid-fluid interaction with particles around brush
    - Avoid over-smoothing from grid sampling in semi-Lagrangian advection
  - Color mixing



(a) Grid-based liquid (b) Hybrid liquid

Hybrid vs. Grid-only

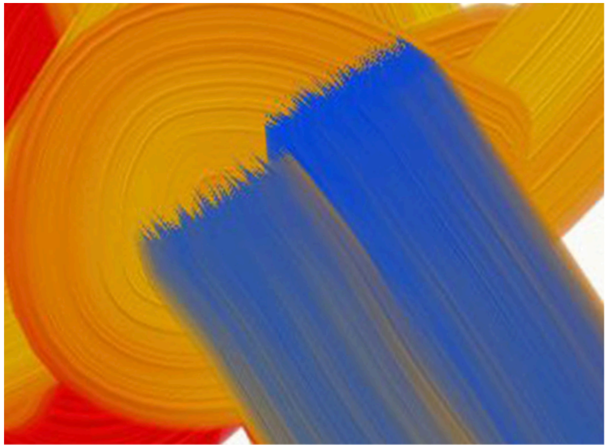
- Hybrid method reveals more details in
  - Surface shape
    - Subpixel level solid-fluid interaction with particles around brush
    - Avoid over-smoothing from grid sampling in semi-Lagrangian advection
  - Color mixing
    - Particles carryings different pigment are not merged immediately
    - Avoid over-smoothing from sampling brush transfer texture



(a) Grid-based liquid (b) Hybrid liquid

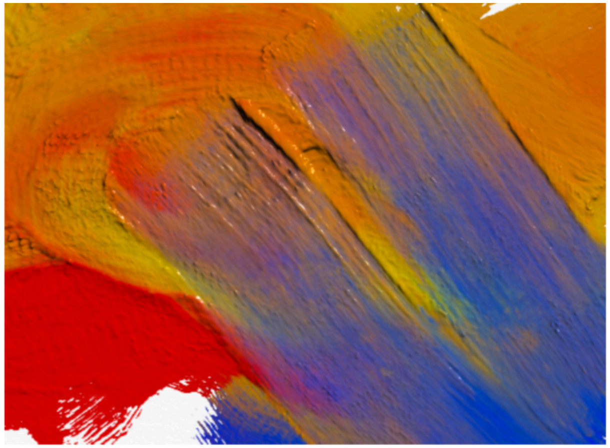
Results

Results



(a) ArtRage 4

(b) Fresh Paint



(c) Our system

- Compared with popular painting software
  - Better 3D shape
  - Finer surface details
  - More pigment variations along strokes

Results

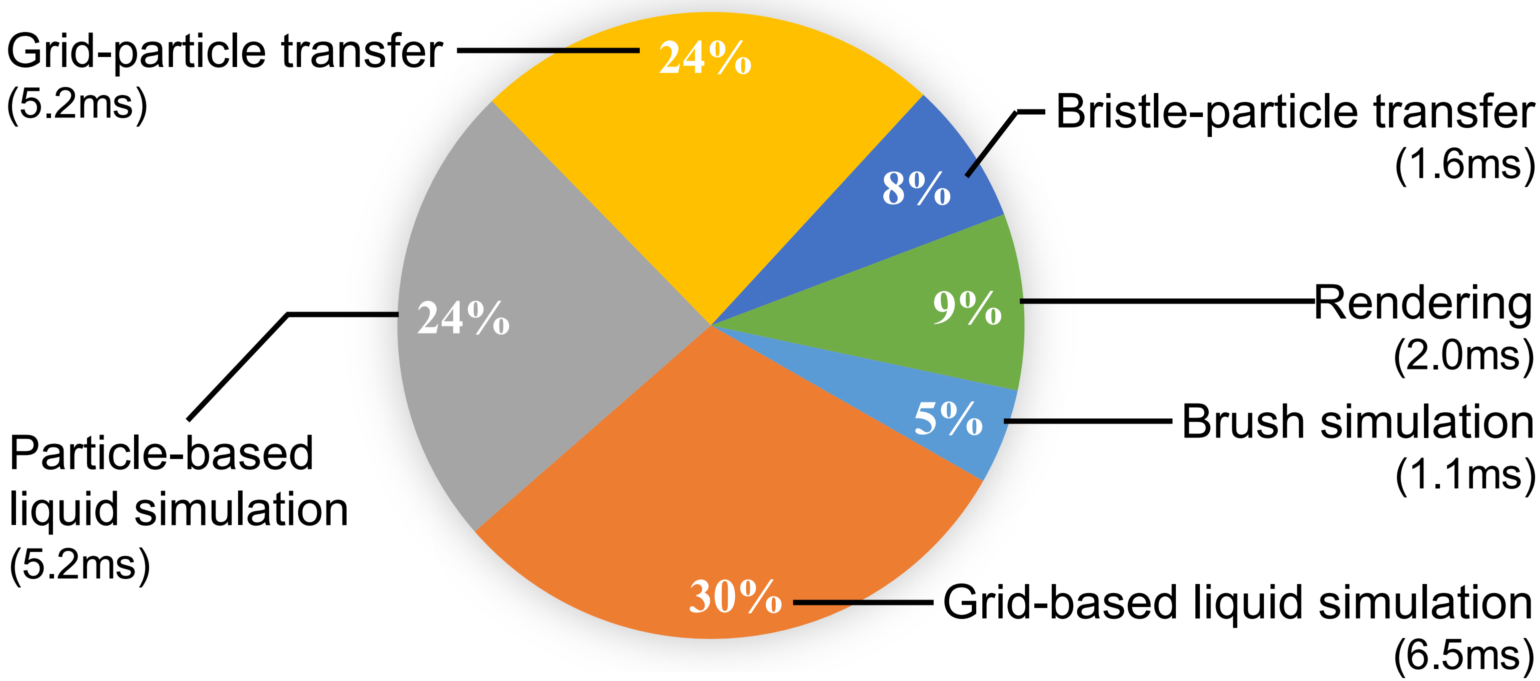
Thick “Impasto” Style
A lot of overhang

Results

Thinner painting style

Performance

- Implemented in CUDA
- GTX Titan X
- Average: 46 fps, 210K Particles (~3M at maximum)



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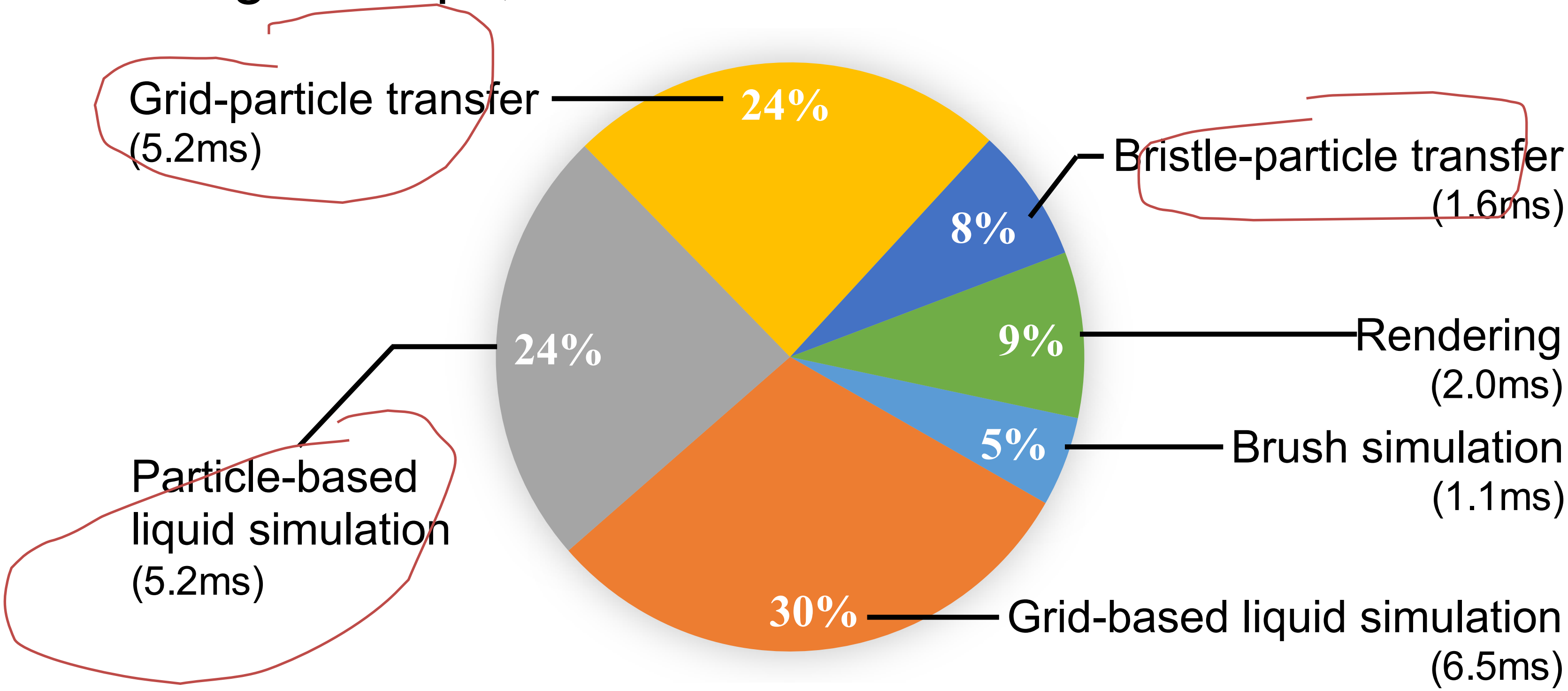

Limitations

- Shear thinning fluid behavior not modelled
- Particles have to be densely sampled
  - for less noisy color mixing
  - 27 particles per cell
- No strict incompressiblity for particle fluid
  - Using velocity field with FLIP/PIC
  - Particles not evenly distributed overtime, resulting in noisy surface
- Some behaviors are more difficult for user control
  - Deposit rate, etc. more difficult to control than with procedural system
- Requirement of high-end graphics hardware

Future Work

- Optimization of implementation
- Unified simulation of watercolor, oil painting, etc
- Simplification and optimization for low-end devices
- Less exhaustive method for similiar quality


Thank you!