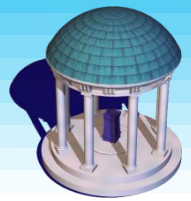


Virtual Painting

http://gamma.cs.unc.edu/DAB

http://gamma.cs.unc.edu/IMPASTO

http://gamma.cs.unc.edu/VISCOUS

http://gamma.cs.unc.edu/BRUSH

Digital Painting

Alvy Ray Smith and Ed Ernshwiller working on "Paint", 1979

Many advantages

- Undo mistakes
- Perfect copies
- Unlimited reprints
- No material cost
- No drying
- No fading or decay
- No physical limits

Traditional Painting

- **Rich, dynamic behavior**
  - Deformable brushes
  - Fluid paint
- **Intuitive control**
  - 3D input
  - Visual and haptic feedback

→ **The *process***

"The dispatch with which a number of effects can be obtained by a direct, simple technique" – *Mayer 1991, The Artist's Handbook*

Goal

- **Enable realistic interactive painting on computer with thick medium using realistic 3D brushes**



Applications

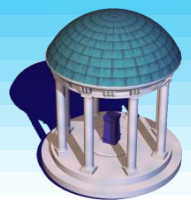
- Training
- Education
- Entertainment
- Production

Artist's Quote

"My artist's toolbox has oils and acrylics—and a computer. But the computer's not tactile, and I miss that. You can't push junk around."

– *Tia, Pixar Animation Studios*

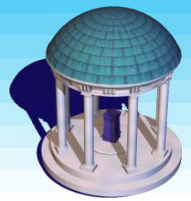
http://www.pixar.com/artistscorner/tia/interview.html



Artist's Quote

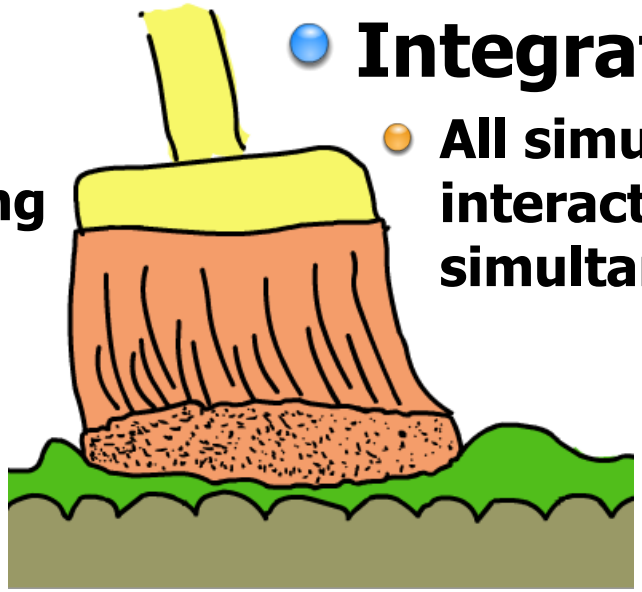
"I have used painter and psp [Paint Shop Pro] for a few yrs, and would **welcome something better, would fight for, would almost die for** a program like is described."

--received by email 8/27/04



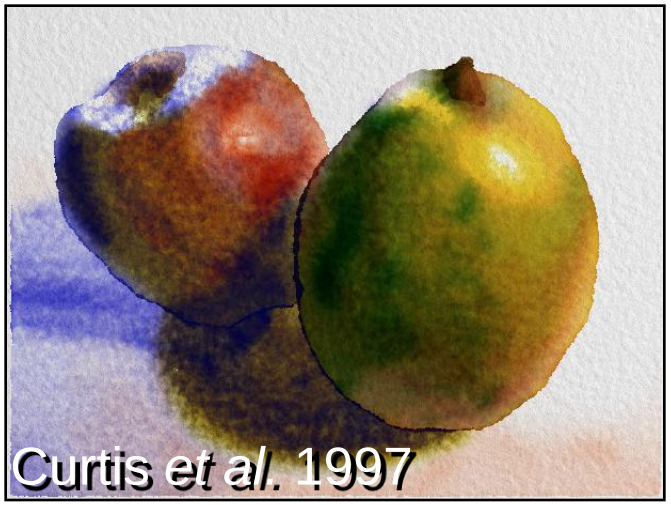
Problem Overview

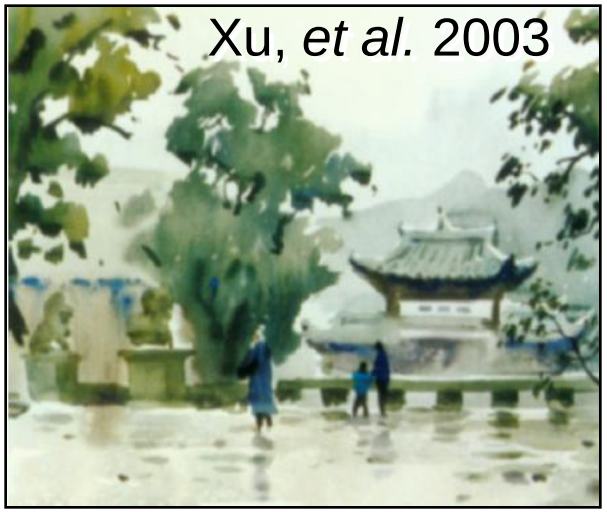
- **Brush**
  - Complex geometry
  - Stiff dynamical system
- **Paint**
  - Complex surface
  - Complex behavior
  - Subsurface scattering
- **Haptics**
  - Needs stability
  - Needs kHz updates

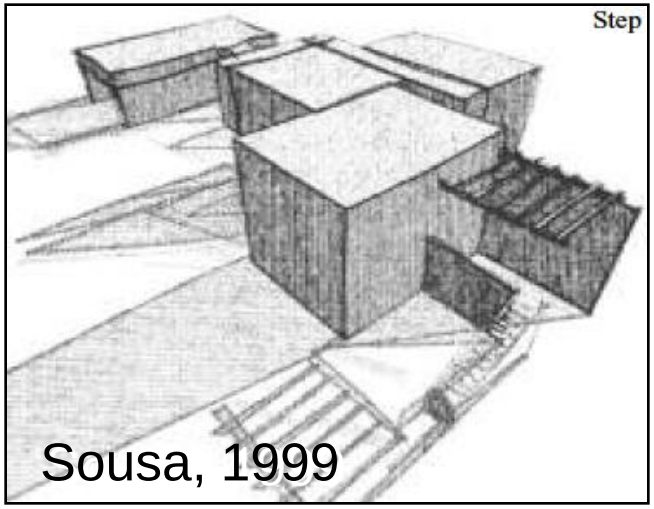


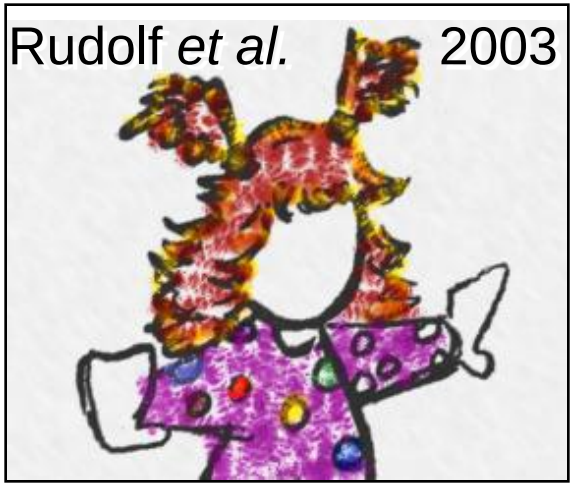
- **Interaction**
  - Canvas ⇔ Brush contact
  - Canvas ⇔ Brush transfers
- **Integration**
  - All simulations must work interactively simultaneously

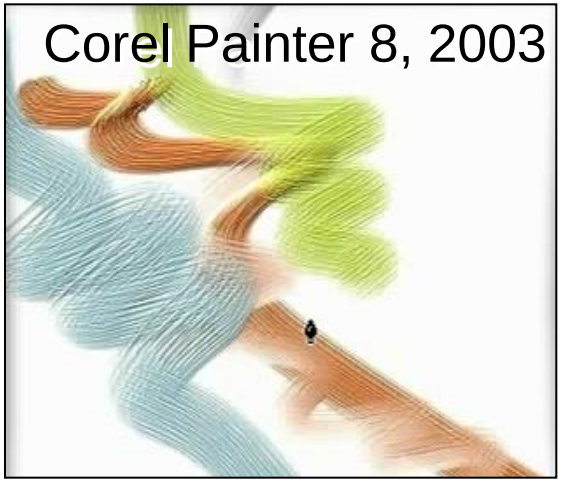
Natural Media



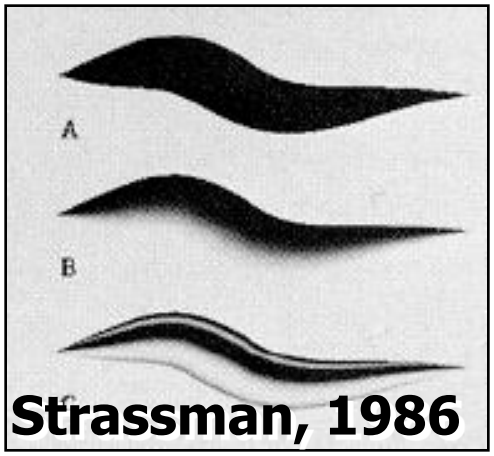


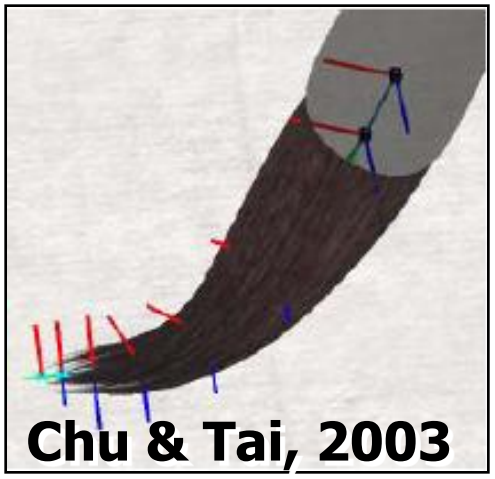




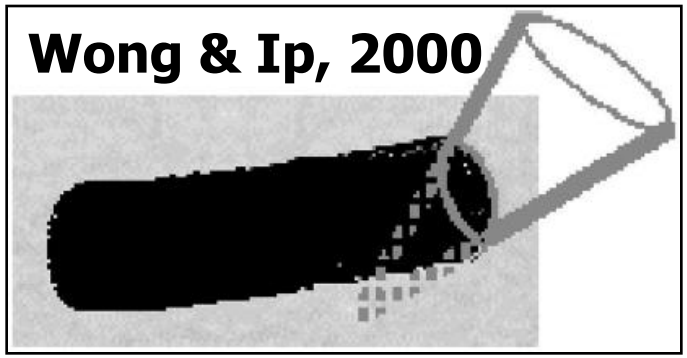


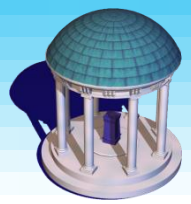
Brush Simulation



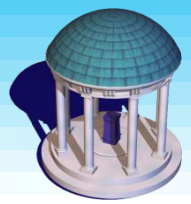


- Only for ink painting
- Specialized geometry
- Lower stiffness
- No real bristles
- No paint pickup
- Some not interactive

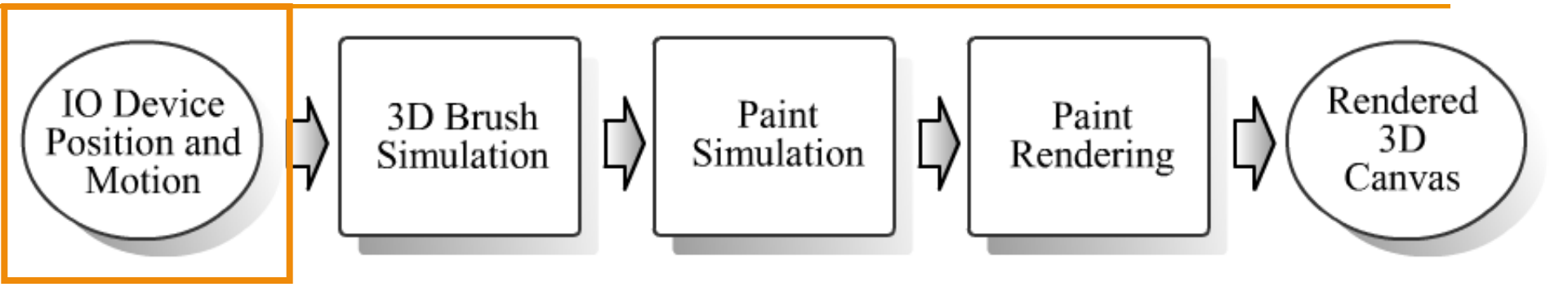


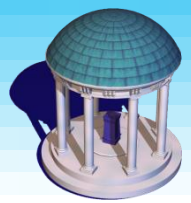


System Context

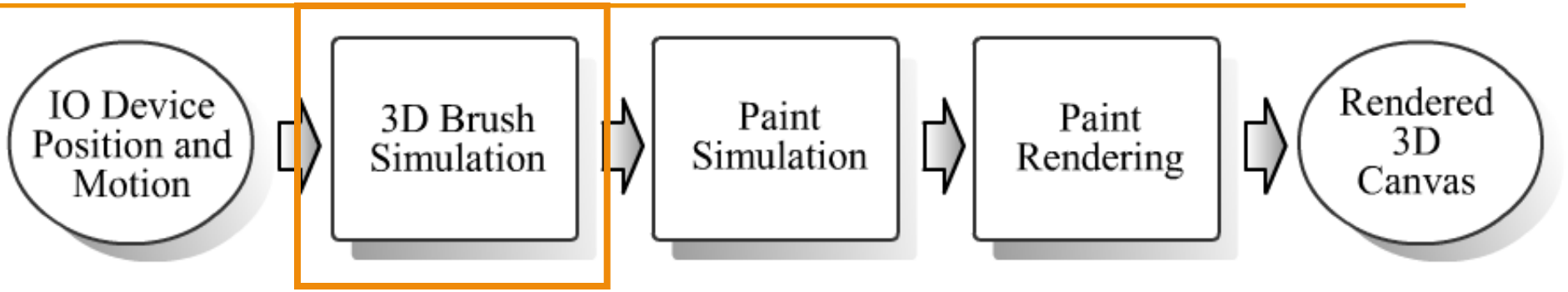


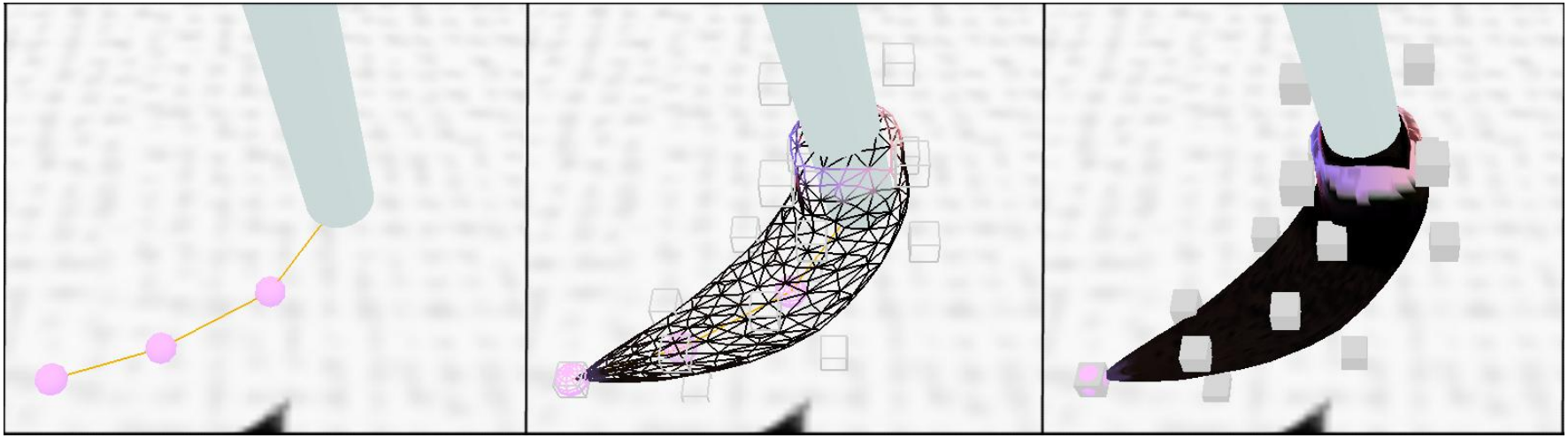
Input

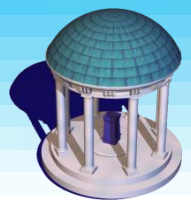

IO Device Position and Motion
3D Brush Simulation
Paint Simulation
Paint Rendering
Rendered 3D Canvas



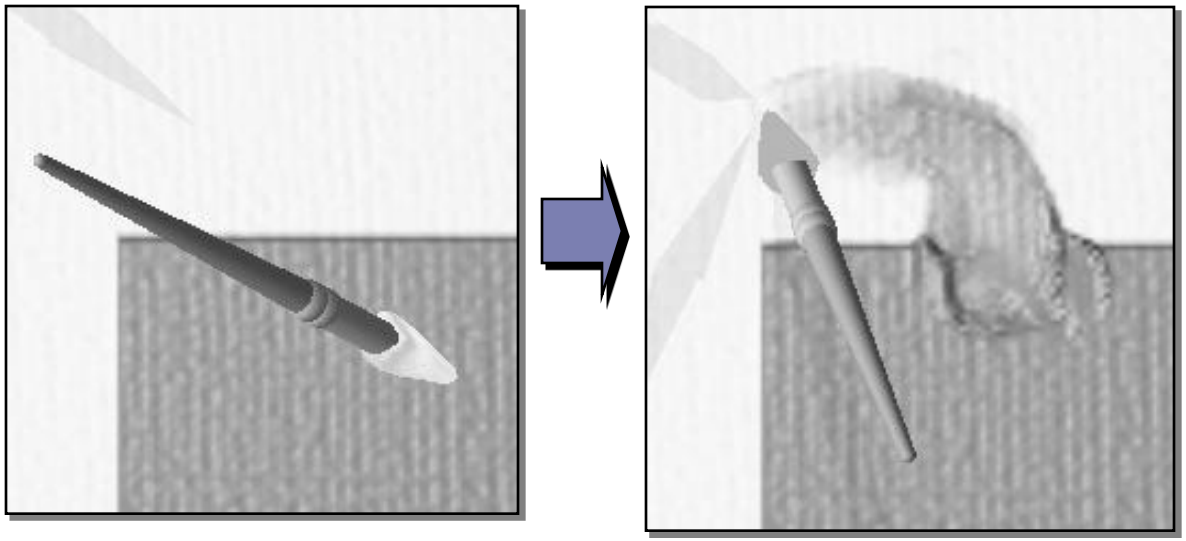
Brush Simulation

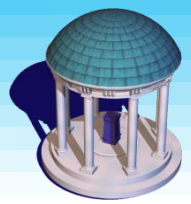




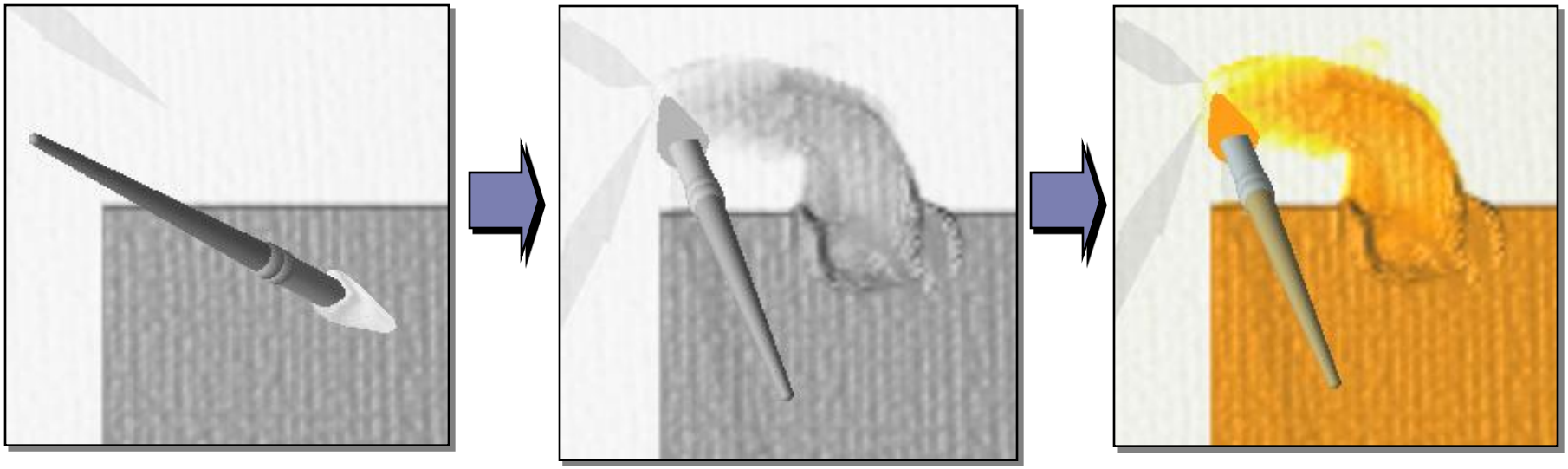


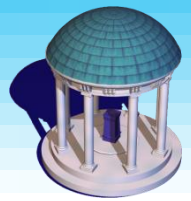
Paint Simulation



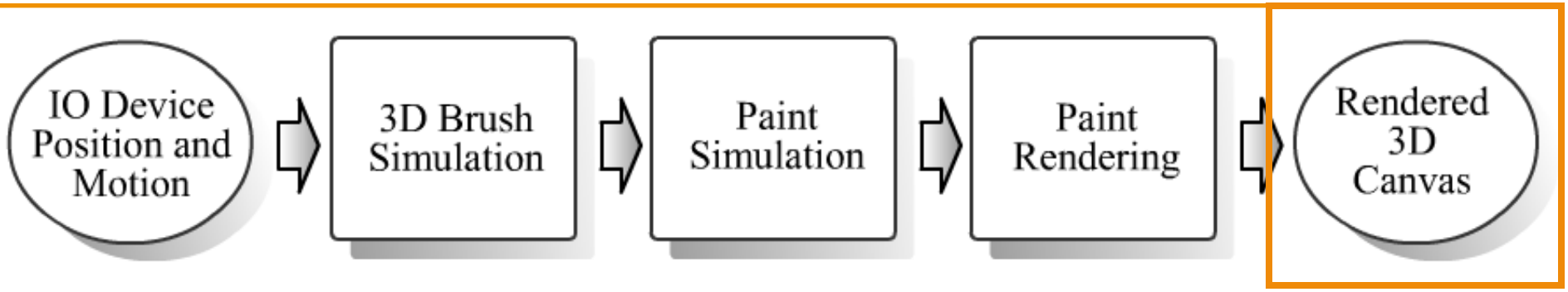


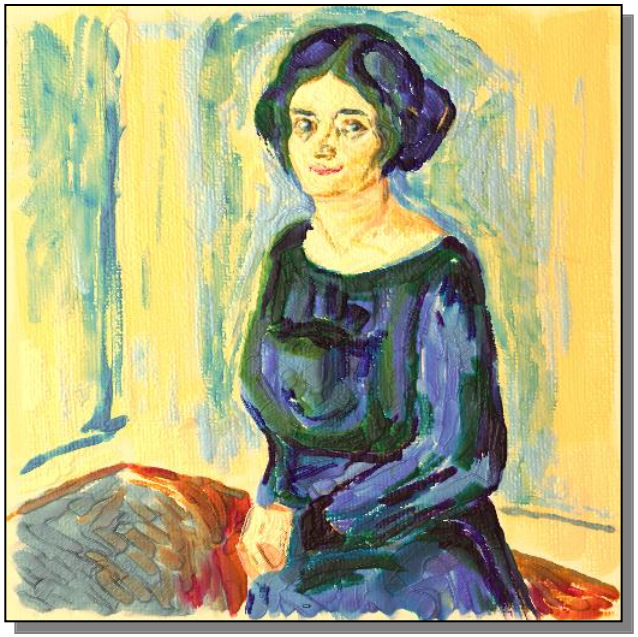
Paint Rendering

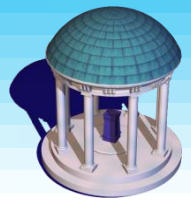




System Overview

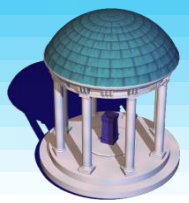






System Demonstration

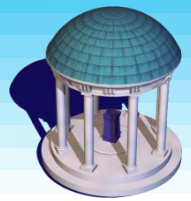
http://www.youtube.com/watch?v=tZq-cpeZm8Q



Brush Modeling

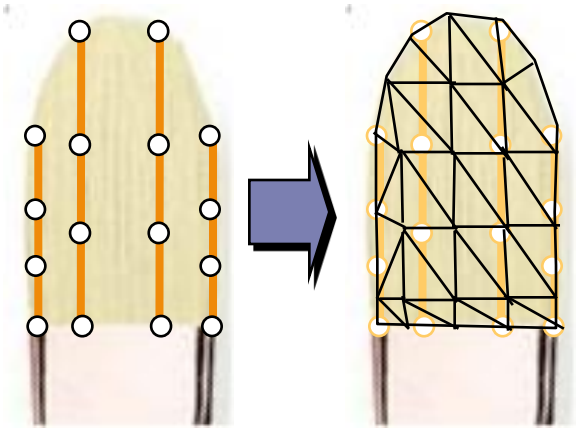
- **Geometric modeling**
  - Brush has 1,000's of hairs
  - Each interacts with paint & roughness/tooth of canvas

- **Dynamic simulation**
  - Each hair deformable and independent
  - Bristles have stiff dynamics

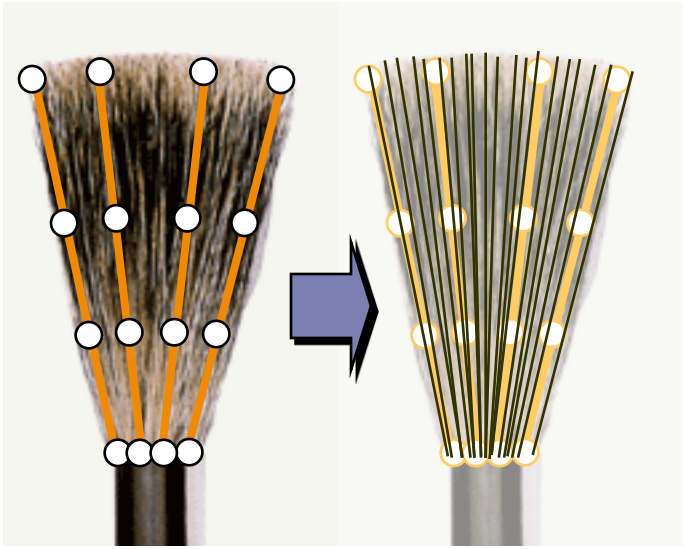


Geometric Modeling

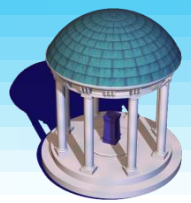
- **Exploit bristle coherence**
- **Define skeletal "spine" bristles**
- **Deform surface** or **interpolate bristles**



For smoother, neater marks

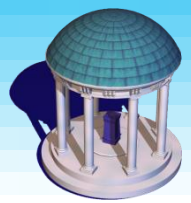


For coarser, rougher marks



Brush Spine Dynamics

- Stiff dynamical system
- Force large, mass small
- Numerical integration requires small timestep

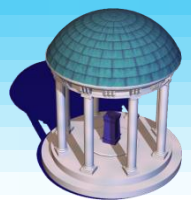


Minimization Approach

- **Brush always at equilibrium so**

$$F = M\ddot{x} \Rightarrow F = 0$$

- **A *statics* problem**
  - Or *quasi-static* since $\dot{x} \neq 0$
- $F = 0 \Rightarrow$ **Energy min**
- **Use standard, robust minimizer**
  - E.g. Quasi-Newton SQP (Sequential Quadratic Programming)



Brush Energy Minimization

- **Minimize**

$$E(\Theta, \Phi) = E_s + E_f + E_d$$

- **where**

$$E_s(\Theta, \Phi) = \sum_i K_i \beta(\theta_i, \phi_i)^2/2$$

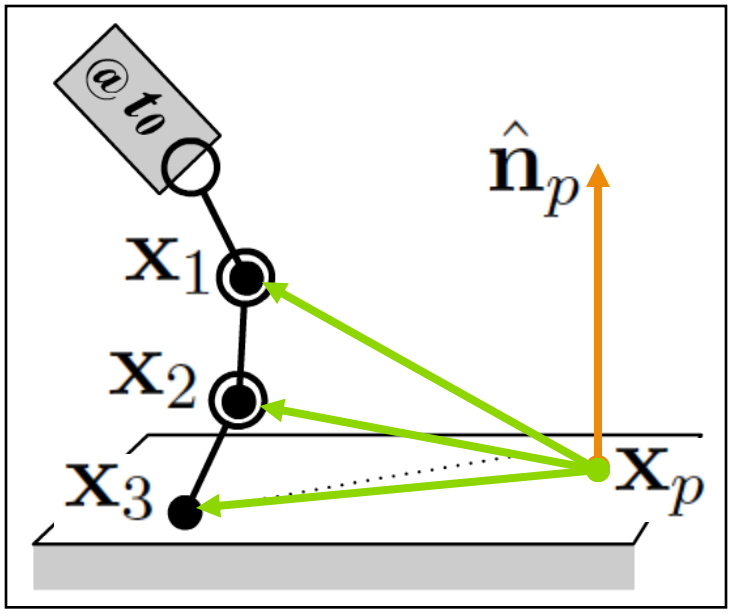
Spring energy

$$E_f(\Theta, \Phi) = \sum_i \mu |F_{n,i}| \|\Delta \mathbf{x}_{c,i}\|$$

Friction loss

$$E_d(\Theta, \Phi) = \sum_i D_i |\Delta \beta_i|$$

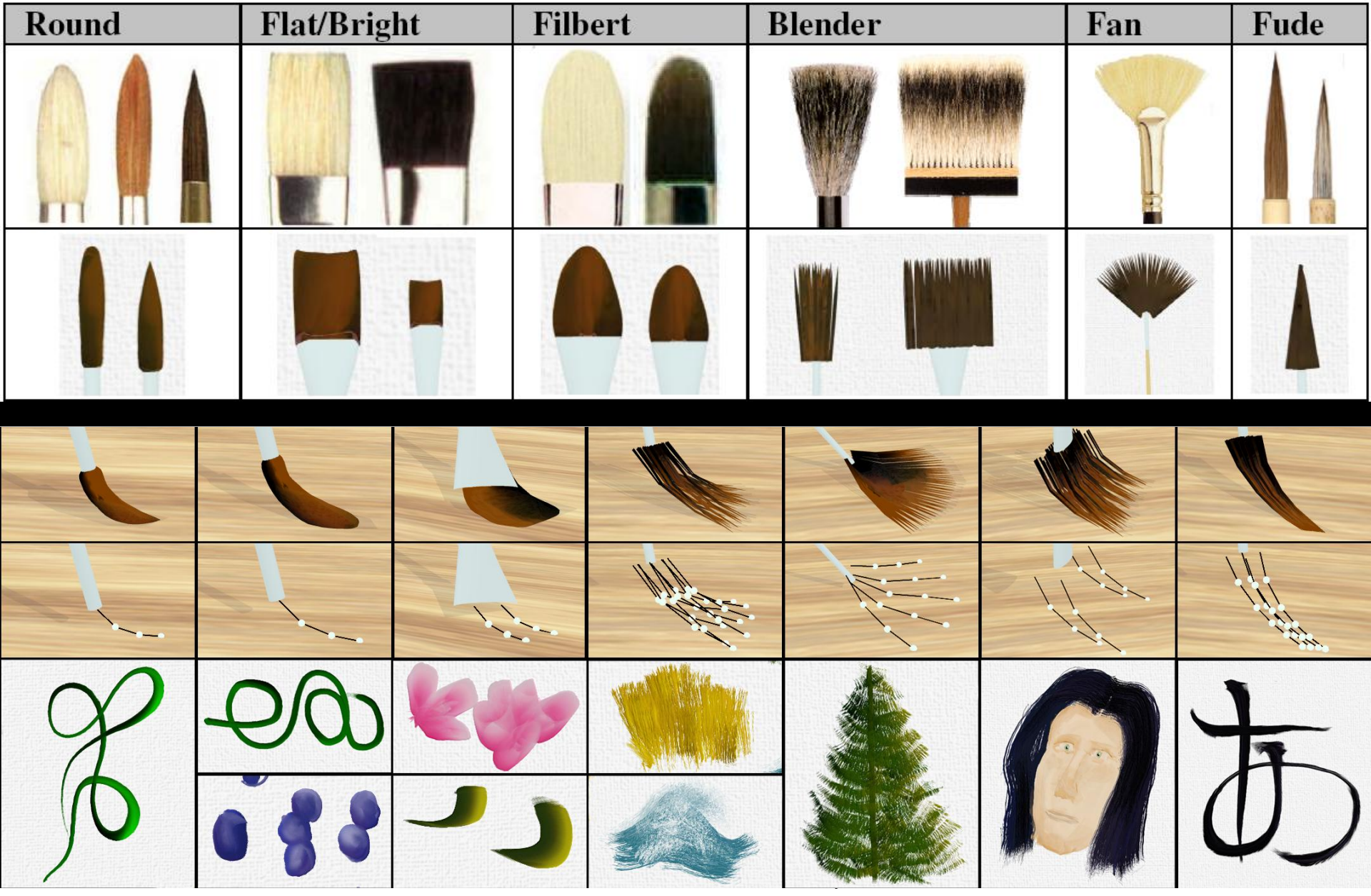
Damping loss

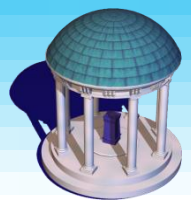


- **Subject to**

$$(\mathbf{x}_i - \mathbf{x}_p) \cdot \hat{\mathbf{n}}_p \geq 0$$

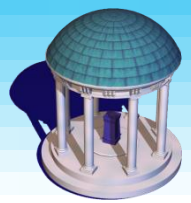
Brush Modeling Results





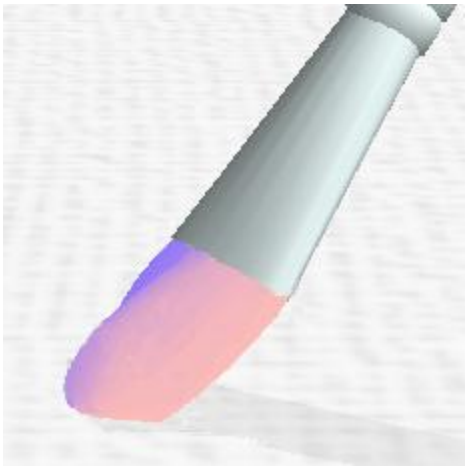
System Demonstration

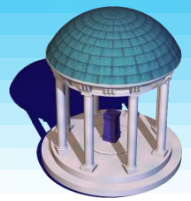
Video



dAb Paint Simulation

- Fast and simple
- 2D paint behavior
- Modest system requirements
- First bi-directional brush transfer
- First complex loading

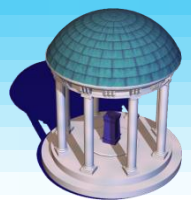




Complex brush loading

- Enabled by 3D brush model + bi-directional transfer
- An essential technique in traditional painting
- Difficult previously
- Useful component of interface

Virtual Painting



dAb Result Images

Frog

Rebecca Holmberg

Apple

Sarah Hoff

Meadow

Rebecca Holmberg

Man

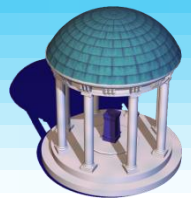
Lauren Adams

Blossoms

Eriko Baxter

Road Bug

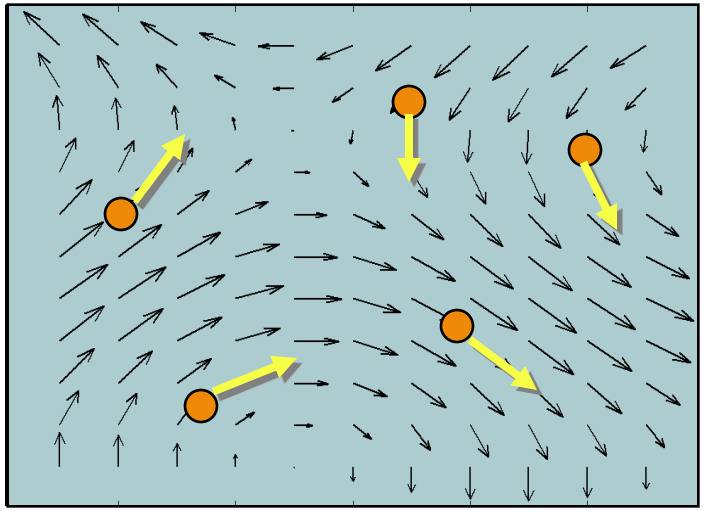
Rebecca Holmberg

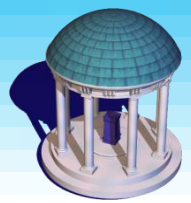


Fluid Motion

Steps:

- **Determine velocity field**
- **Advect material**





Simulating Paint - Velocity

- **Paint is a Viscous / Viscoplastic Fluid**

$$\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\text{acceleration}} = \underbrace{-(\mathbf{v}\cdot\nabla)\mathbf{v}}_{\text{advection}} \underbrace{-\nabla p}_{\text{pressure}} \underbrace{+\nu\nabla^2\mathbf{v}}_{\text{viscosity}} \underbrace{+\mu_e\nabla\cdot\boldsymbol{\sigma}}_{\text{elasticity}} + \mathbf{F}$$

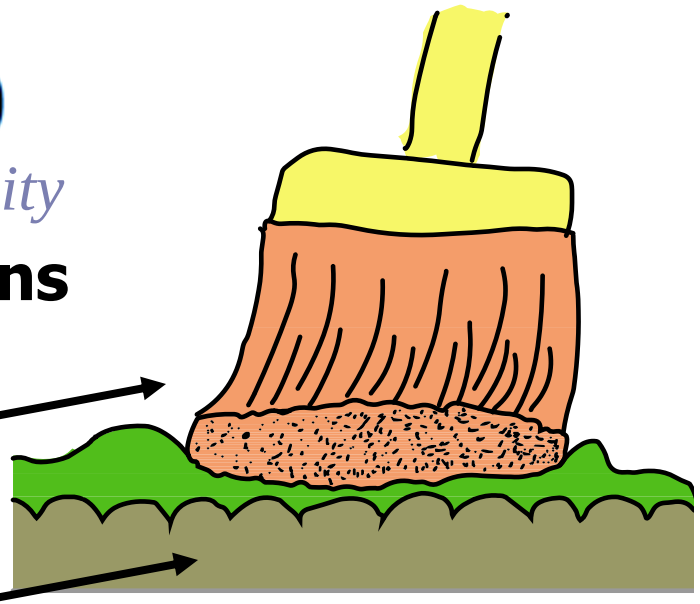
$$\nabla \cdot \mathbf{v} = 0$$

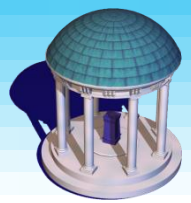
incompressibility

Subject to boundary conditions

$$\mathbf{v} = \mathbf{v}_{\text{brush}} \quad \in \partial\Omega_{\text{brush}}$$

$$\mathbf{v} = \mathbf{v}_{\text{canvas}} \quad \in \partial\Omega_{\text{canvas}}$$



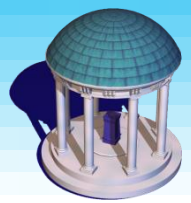


Material Advection

- **Given velocity field $\mathbf{v}$, move material according to the advection equation:**

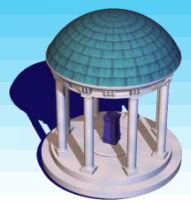
$$\frac{\partial q}{\partial t} = -(\mathbf{v} \cdot \nabla) q$$

- **Material =** Pigment & φ field
- **Semi-Lagrangian advection**



System Demonstration

Video



Viscous Result Images

Woman in a Hat

Eriko Baxter

Field of Flowers

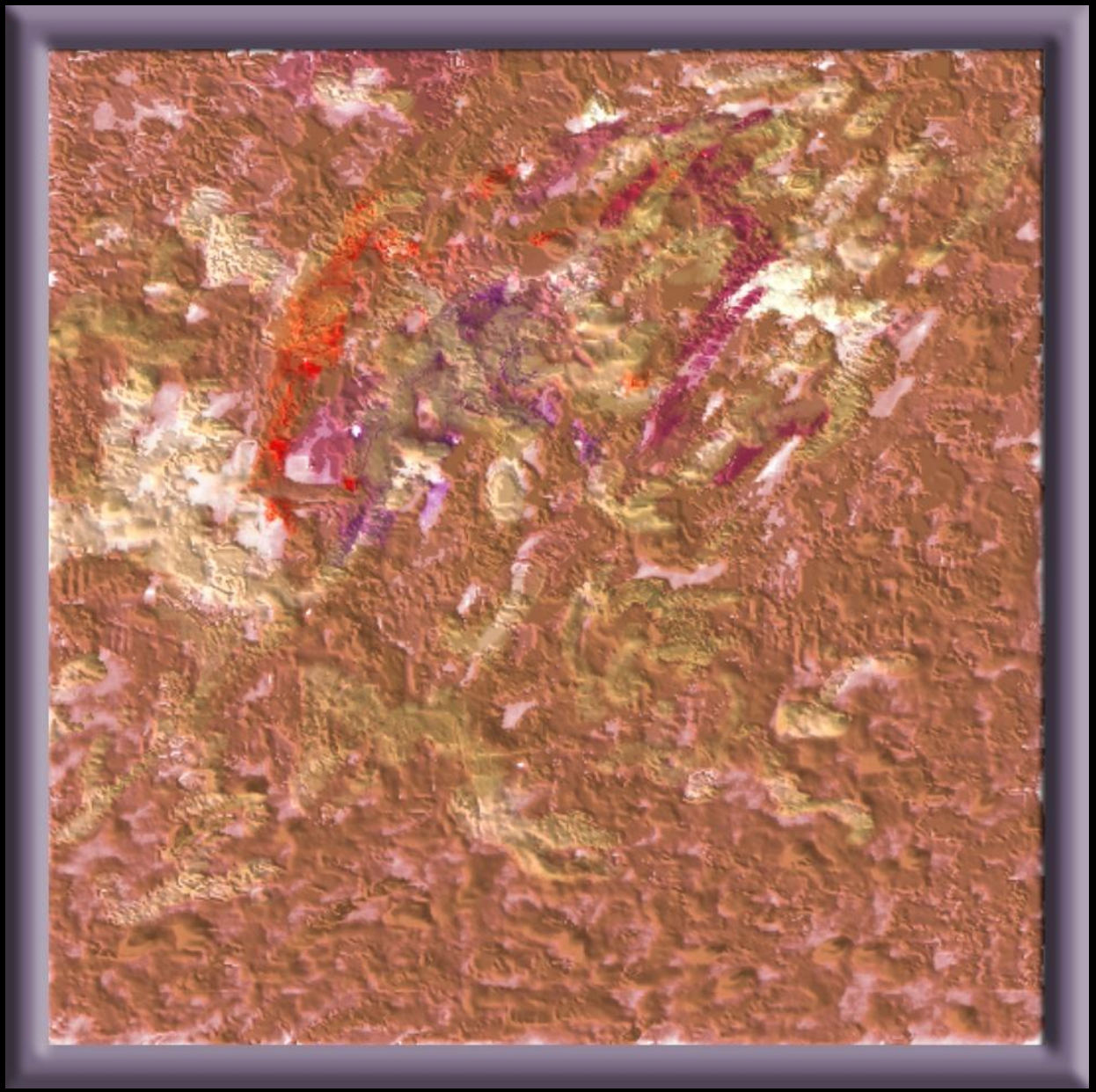
Eriko Baxter

The Beach

Andrea Mantler

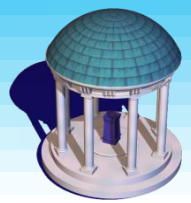
Meadow

Haolong Ma



Abstract I

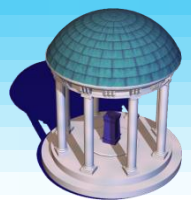
John Holloway



IMPaSTo Paint Dynamics

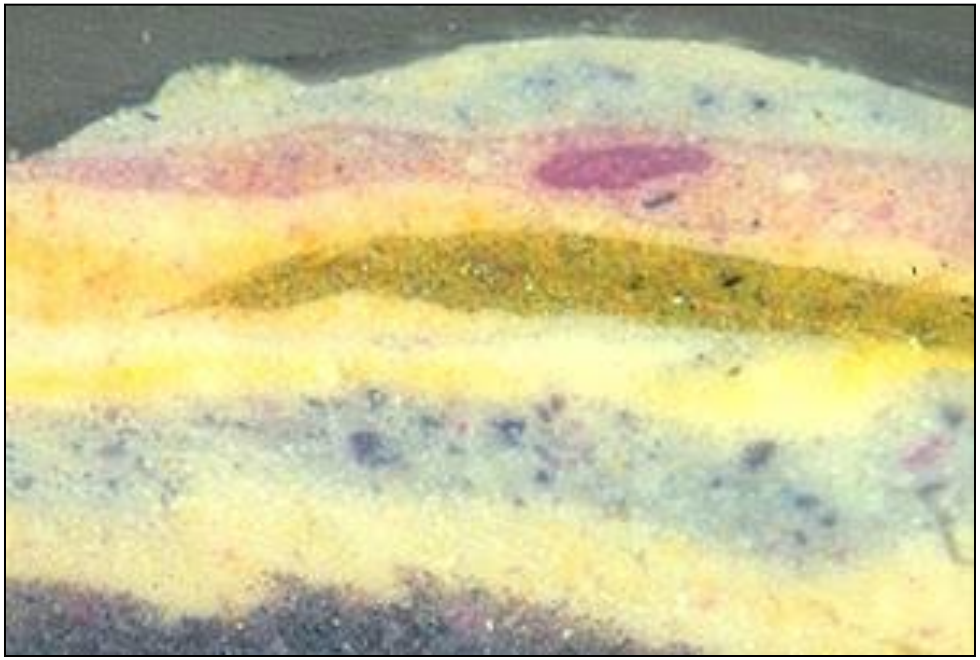
- **Paint is very complex**

- **IMPaSTo strategy: Model *dominant* terms**

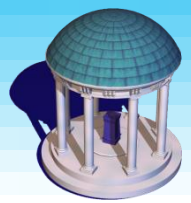


2.5D Representation

- Cross section of Monet's *Water Lillies*



(Courtesy The Museum of Modern Art)



Simulating Paint - Velocity

- **Paint is a Viscous / Viscoplastic Fluid**

$$\frac{\partial \mathbf{v}}{\partial t} = -(\mathbf{v}\cdot\nabla)\mathbf{v} - \nabla p + \nu\nabla^2\mathbf{v} + \mu_e\nabla\cdot\boldsymbol{\sigma} + \mathbf{F}$$

acceleration — *advection* — *pressure* — *viscosity* — *elasticity*

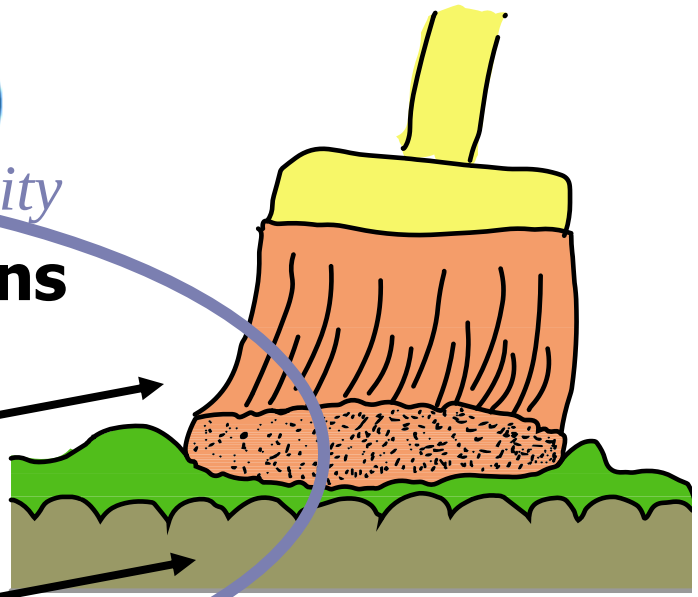
$$\nabla\cdot\mathbf{v} = 0$$

incompressibility

Subject to boundary conditions

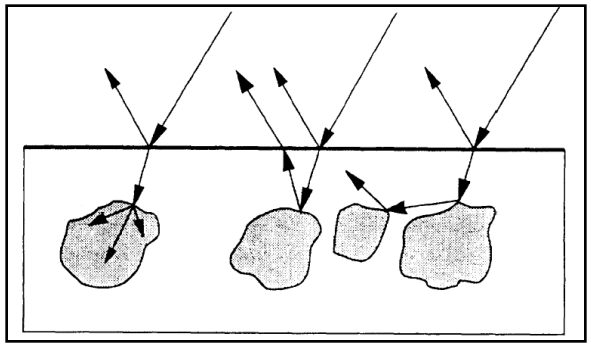
$$\mathbf{v} = \mathbf{v}_{\text{brush}} \quad \in \partial\Omega_{\text{brush}}$$

$$\mathbf{v} = \mathbf{v}_{\text{canvas}} \quad \in \partial\Omega_{\text{canvas}}$$



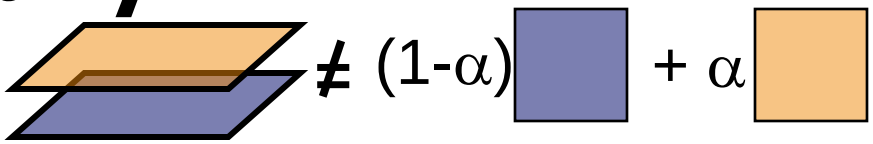
Paint Color

- Pigmented material
- Subsurface scattering



- Mixes nonlinearly:

- Composites nonlinearly:

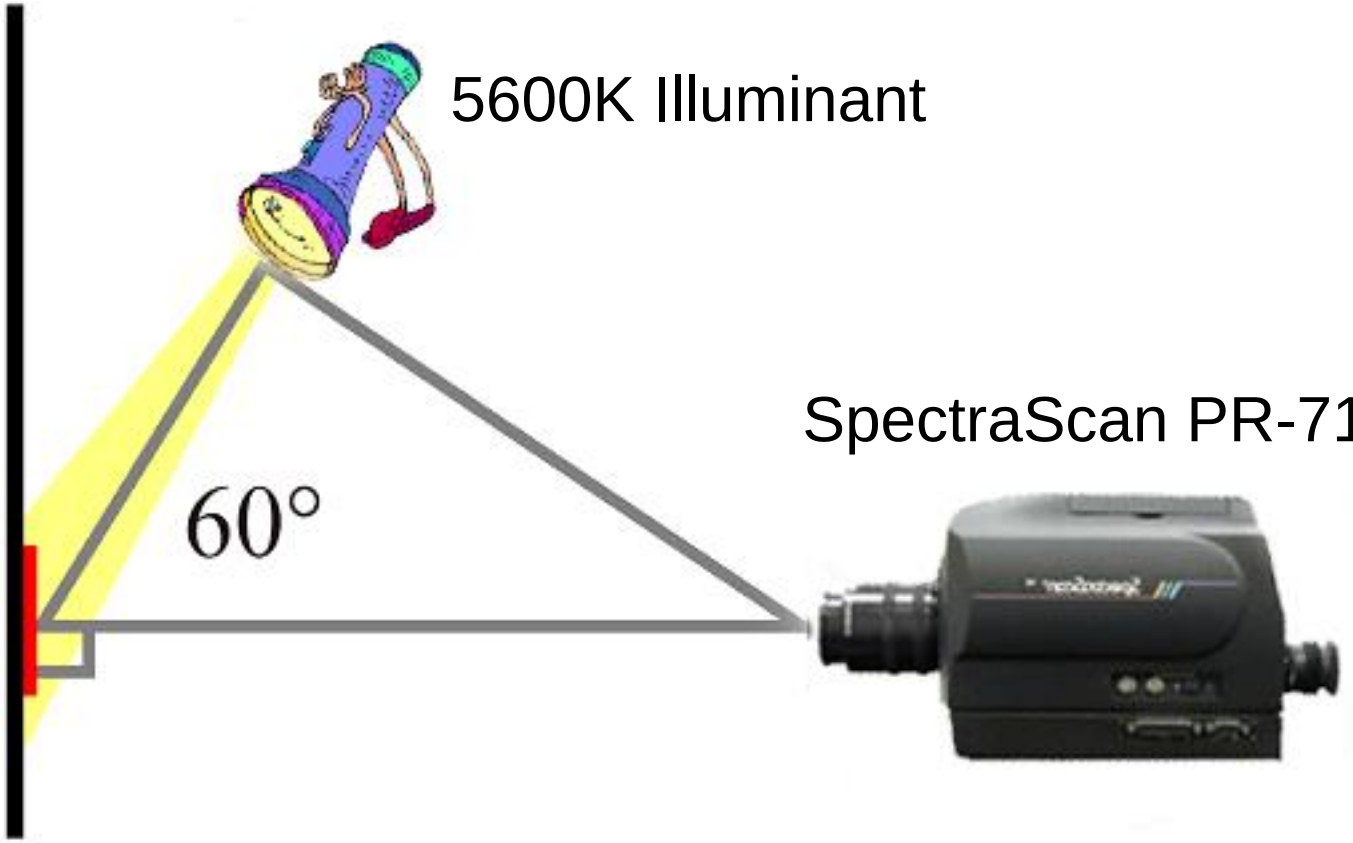


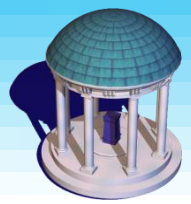
- Kubelka-Munk model (1948,1954)

$$R_\infty = 1 + \frac{K}{S} - \sqrt{\left(\frac{K}{S}\right)^2 + 2\frac{K}{S}}$$

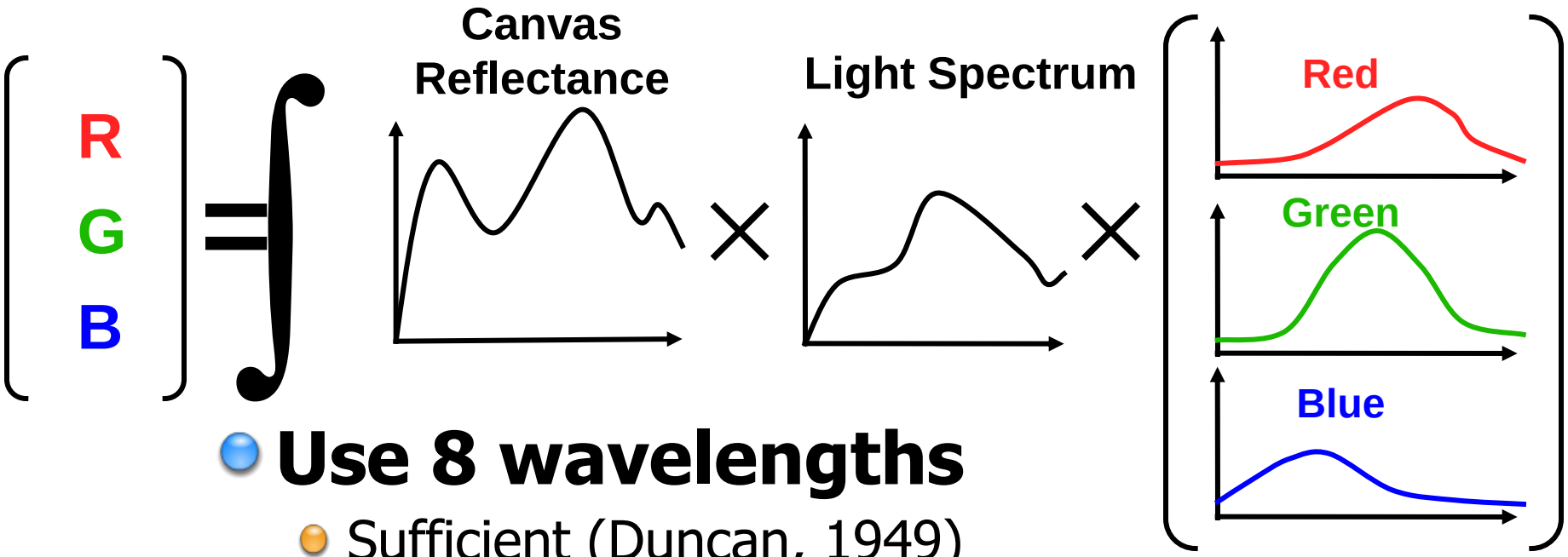
Measurement

- **Data collection setup**

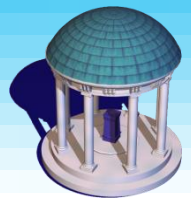




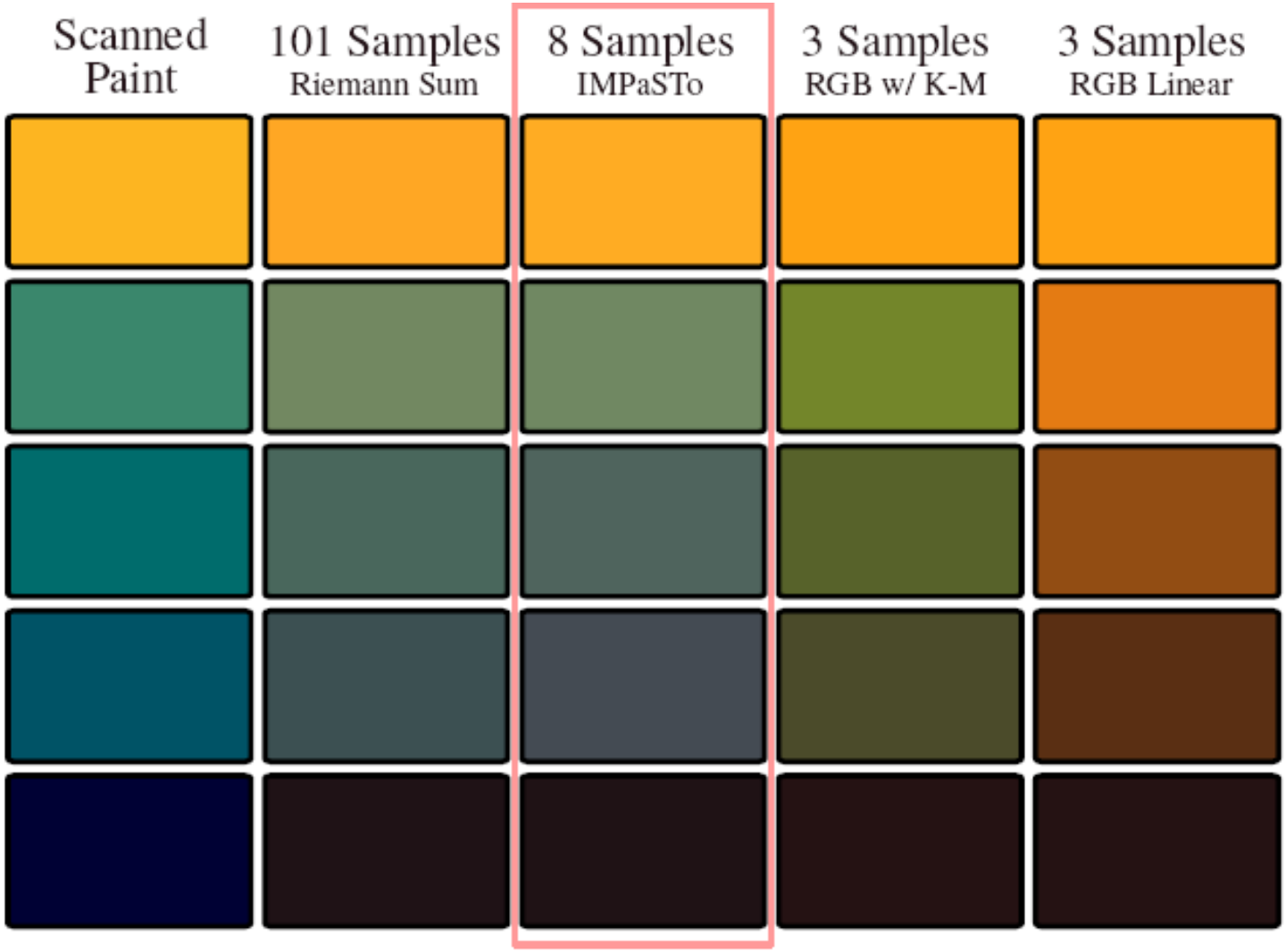
Spectral Sampling

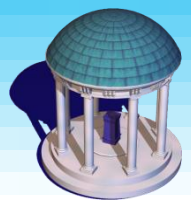


- **Use 8 wavelengths**
  - Sufficient (Duncan, 1949)
  - Efficient on GPU
- **Gaussian quadrature**
- **Choose best 8 at runtime**



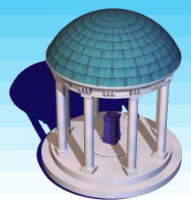
Color Mixing Results





System Demonstration

Video



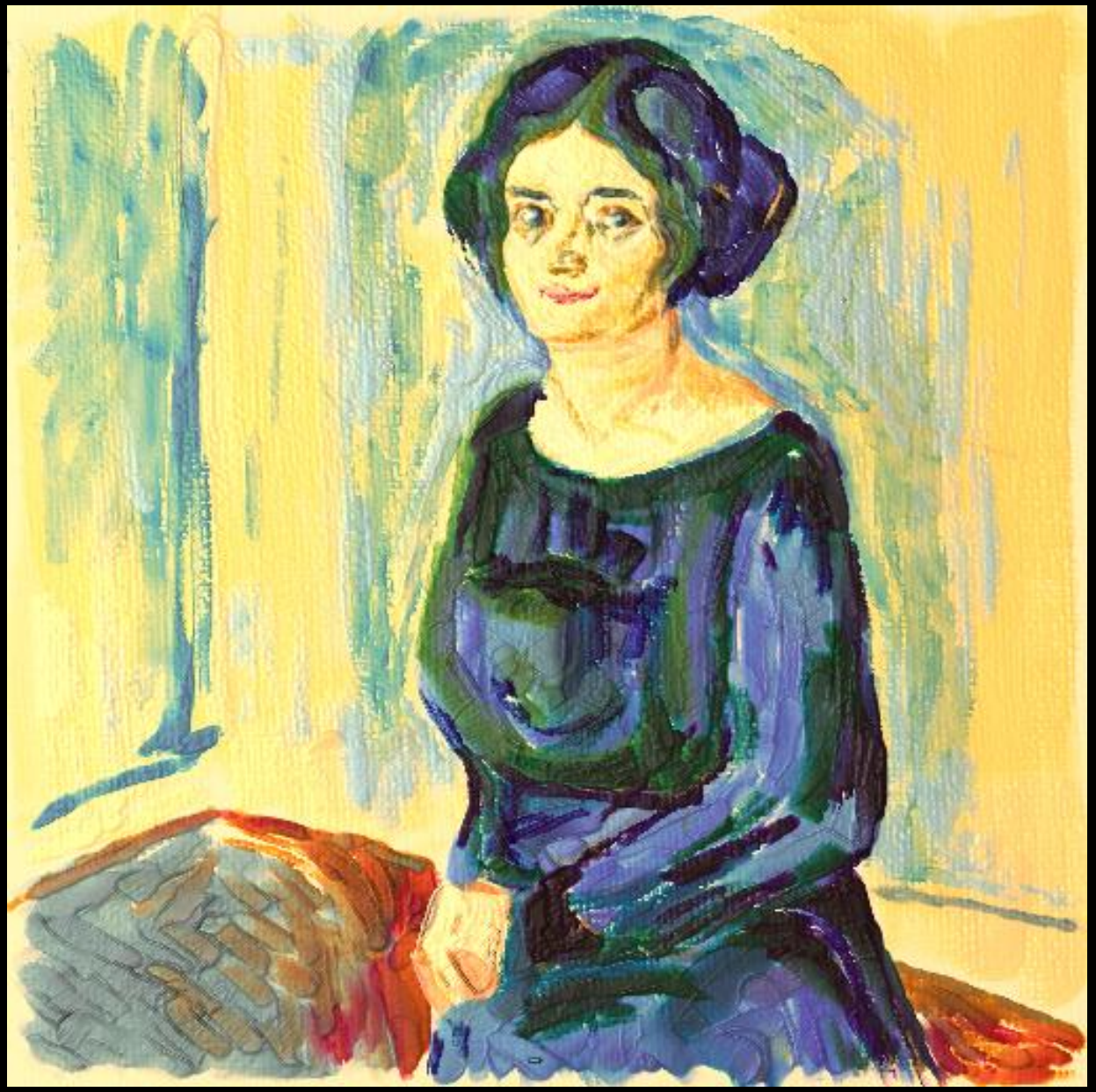
IMPaSTo Result Images

Ajisai

Eriko Baxter

Woman

Andrea Mantler

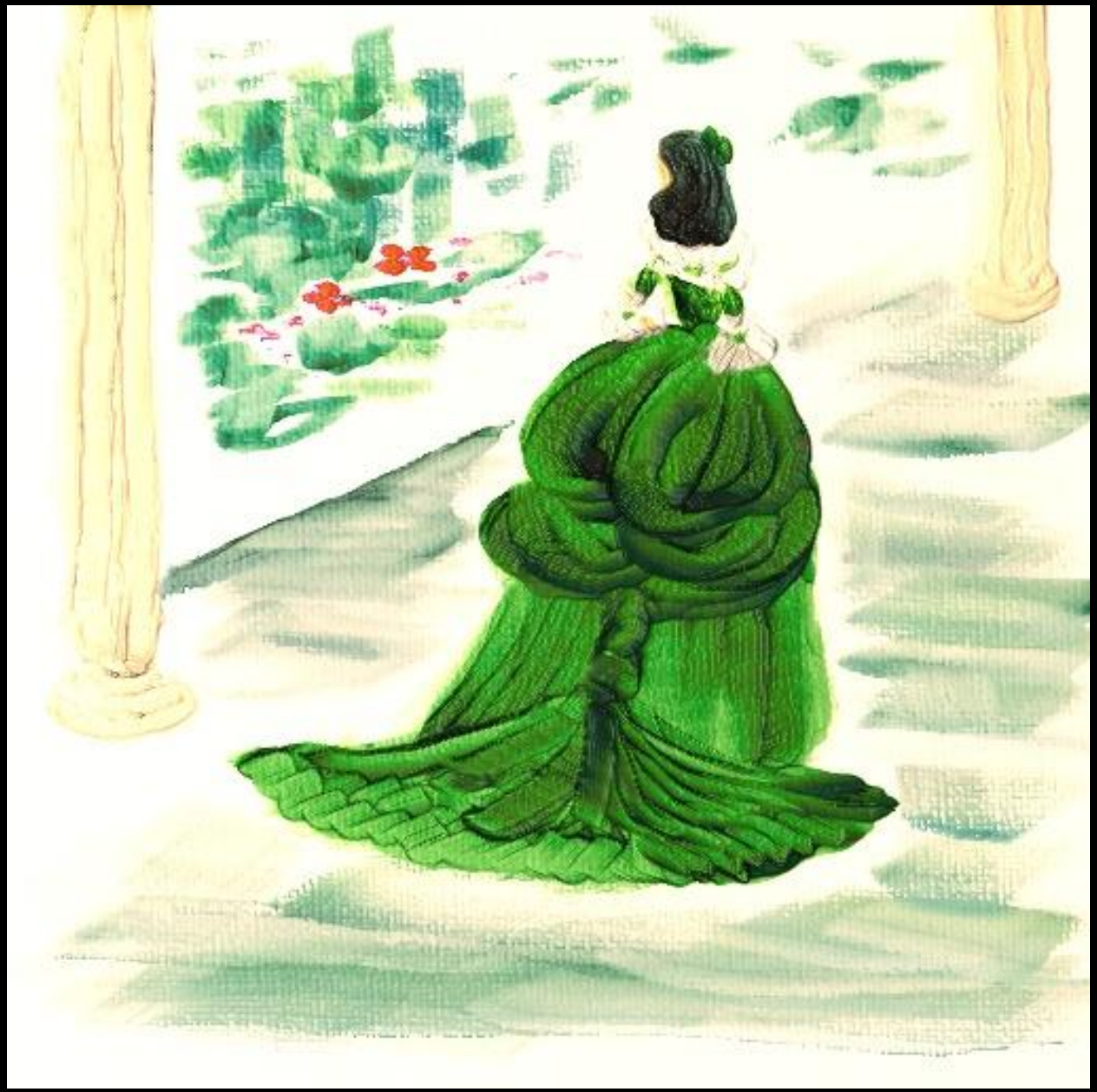


Dame en Blau

Heather Wendt

Gogh Studios
Room 1

William Baxter



Green

Eriko Baxter

Abstract III

John Holloway