Target-Driven Smoke Animation

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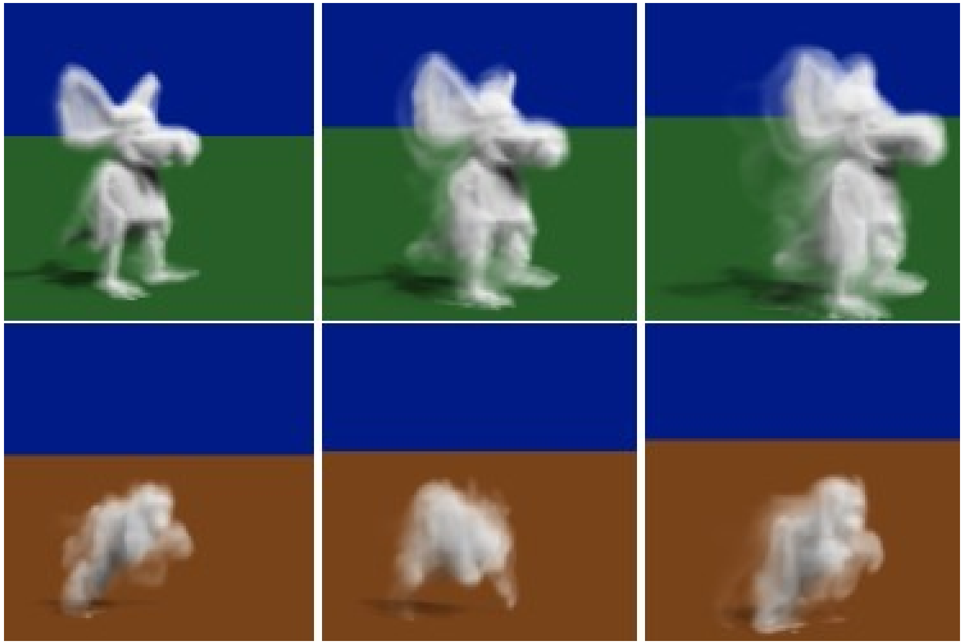
presented by Ivan Appert



Outline

- Fluid Dynamics
- Previous Work
- Algorithm
- Results
- Limitations
- Discussions

Fluid Dynamics

- fluid dynamics are used for animation of:
  - liquid
  - smoke
  - fire
- Navier-Stokes
  - with viscosity
- Euler equations
  - without viscosity

Fluid Dynamics
Problems

- realistic simulations
  - [Stam, 1999, Stable Fluids]
  - [Fedkiw, Stam, Jensen, 2001, Visual Simulation of Smoke]
- **BUT:**
  It's hard to control the outcome of the simulation or to give some underlying meaning
  - eg: let a cloud change into a face

Previous Work

- Controlling Fluid Animation
  [N. Foster and D. Metaxas, 1997]
- Computational Fluid Dynamics in a Traditional Animation Environment
  [P. Witting, 1999]
- Structural Modeling of Flames for a Production Environment
  [A. Lamorlette and N. Foster, 2002]

- Drawbacks
  - no direct control over the desired results

Previous Work(2)

- Keyframe Control of Smoke Simulation
  [A. Treuille, A. McNamara, Z. Popovic and J. Stam, 2003]

- uses keyframes
- impressive results
- very computational intensive
  - one complete simulation per evaluation
  - problem grows with length

Algorithm
Overview

- Idea
- Problem Definition
- Equations of Flow
- Modifications
- Numerical Simulation

Algorithm
Idea

- target-driven approach
  - sequence of targets
  - each target as an attractor
  - advancing stepwise to the target
  - using the fluid dynamics equation to ensure smoke like behavior
  - modifications

Algorithm
Problem Definition

- Given
  - initial density of smoke $\rho_0 = \rho(x, 0)$
  - sequence of target densities $\rho_i^* = \rho^*(\boldsymbol{x}, t_i)$
- Target
  - smoke should advance toward target
  - natural and smoke-like manner
  - no matching requirement

Algorithm
Equations of Flow

- Euler equations

$$\boldsymbol{u}_t = -\boldsymbol{u} \cdot \nabla \boldsymbol{u} - \nabla p + \boldsymbol{f}$$

$$\nabla \cdot \boldsymbol{u} = 0$$

  - the velocity vector field: $\boldsymbol{u}$
  - external forces: $\boldsymbol{f}$
  - hydrostatic pressure: p

Equations of Flow(2)

- Advection

$$\rho_t = -\boldsymbol{u} \cdot \nabla \rho$$

  - smoke density field: ρ

Driving Force $\boldsymbol{F}(\boldsymbol{\rho}, \boldsymbol{\rho}^*)$

- desired properties
  - driving the current density towards the target density

    $$\rightarrow \quad \boldsymbol{F}(\rho, \rho^*) \propto \nabla \rho^*$$

    $$\tilde{\rho}^* = G(\boldsymbol{x}) * \rho^* \quad \rightarrow \quad \boldsymbol{F}(\rho, \rho^*) = \rho \frac{\nabla \tilde{\rho}^*}{\tilde{\rho}^*}$$

  - rest if target achieved

    $\rightarrow \quad \boldsymbol{F}(\boldsymbol{\rho}^*, \boldsymbol{\rho}^*)$ must be a gradient of a potential field

Driving Force $\boldsymbol{F}(\boldsymbol{\rho},\boldsymbol{\rho}^*)$ *(2)*

$$\rightarrow \quad \boldsymbol{F}(\rho,\rho^*)=\tilde{\rho}\,\frac{\nabla\tilde{\rho}^*}{\tilde{\rho}^*}$$

- inserted as external force

$$\rightarrow \quad \boldsymbol{u}_t=-\boldsymbol{u}\cdot\nabla\boldsymbol{u}-\nabla p+\boldsymbol{F}(\boldsymbol{\rho},\boldsymbol{\rho}^*)$$

Modifications

Smoke Gathering

- desired properties
  - reduce numerical dissipation
  - generate new density values
- define $e(\boldsymbol{x},t)=\rho(\boldsymbol{x},t)-\rho^{*}(\boldsymbol{x})$
- apply diffusion to *e*

$$e_t=\nabla^2 e$$

$$0=\frac{\delta e}{\delta \boldsymbol{n}}$$

Modifications

Smoke Gathering(2)

- substitute *e*

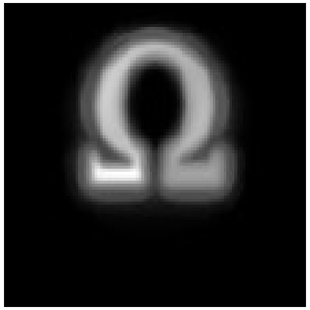
$$\rightarrow \quad \rho_t = \nabla \cdot \nabla (\rho - \rho^*)$$

  - diffuse only the vicinity of the target
  - diffuse only where some smoke is present

$$\rightarrow \quad \boldsymbol{G}(\boldsymbol{\rho}, \boldsymbol{\rho}^*) = \nabla \cdot [\rho \tilde{\rho}^* \nabla (\rho - \rho^*)]$$

- inserted in

$$\rho_t = -\boldsymbol{u} \cdot \nabla \rho + \boldsymbol{G}(\rho, \rho^*)$$



Modifications

Attenuation

- desired properties
  - control the momentum
  - add a viscous-like feature

$$\rightarrow \quad \boldsymbol{u}_t = -\boldsymbol{u} \cdot \nabla \boldsymbol{u} - \nabla p + \boldsymbol{F}(\boldsymbol{\rho}, \boldsymbol{\rho}^*) - v_d \boldsymbol{u}$$

Modifications

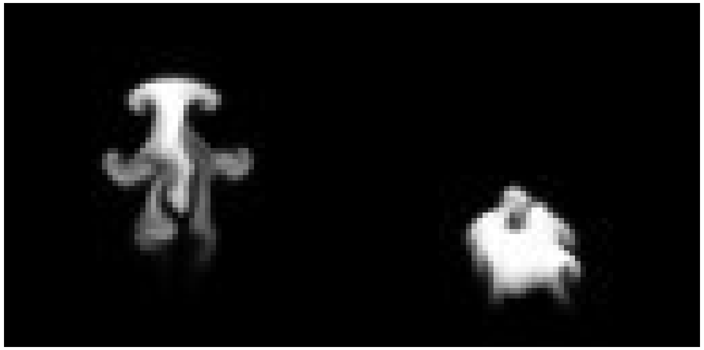
Summary

- Formulas:

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\boldsymbol{u}_t = -\boldsymbol{u} \cdot \nabla \boldsymbol{u} - \nabla p + \boxed{\nu_f} \boldsymbol{F}(\rho, \rho^*) - \boxed{\nu_d} \boldsymbol{u}$$

$$\rho_t = -\boldsymbol{u} \cdot \nabla \rho + \boxed{\nu_g} \boldsymbol{G}(\rho, \rho^*)$$

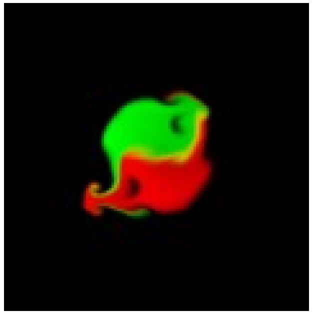


Modifications

Multiple field flow

- more precise control
- split the smoke density field
  - every field with its own initial and target field
  - n driving forces

$$\boldsymbol{F} = \sum \boldsymbol{F}_{\boldsymbol{i}}(\rho^{i}, \rho^{*,i})$$



  - n advection equations

$$\rho_{t}^{i} = -\boldsymbol{u} \cdot \nabla \rho^{i} + v_{g} \boldsymbol{G}(\boldsymbol{\rho}^{\boldsymbol{i}}, \boldsymbol{\rho}^{*,\boldsymbol{i}})$$

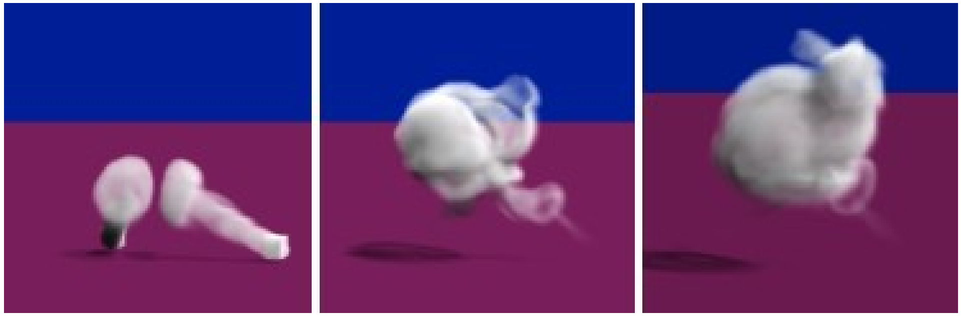
Algorithm

Numerical Simulation

- fractional steps
  - apply driving force: $\boldsymbol{u_t} = v_f \boldsymbol{F}(\rho, \rho^*)$
  - attenuate momentum: $\boldsymbol{u_t} = -v_d \boldsymbol{u}$
  - advect momentum: $\boldsymbol{u_t} = -\boldsymbol{u} \cdot \boldsymbol{\nabla} \boldsymbol{u}$
  - project
    - solve: $\nabla^{2p} = \boldsymbol{\nabla} \boldsymbol{u}$
    - subtract ∇p from **u**
  - advect smoke: $\rho_t = -\boldsymbol{u} \nabla \rho$
  - gather smoke: $\rho_t = v_g \boldsymbol{G}(\rho, \rho^*)$

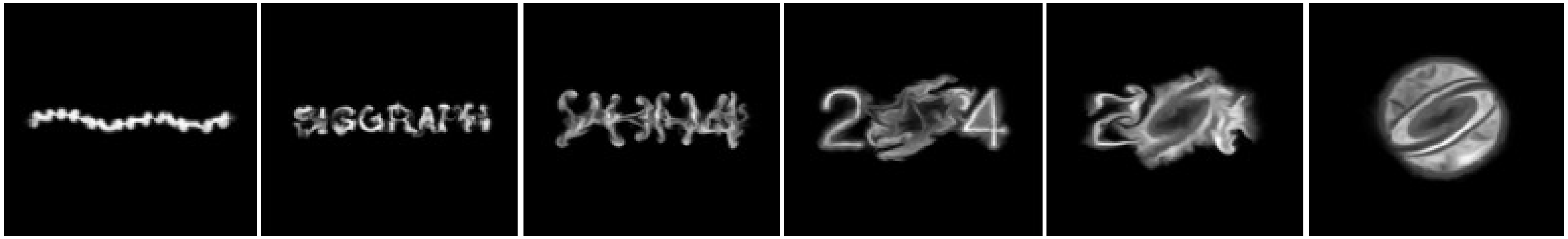
Results

- new control mechanism for smoke animation
  - direct control
  - no low-level knowledge needed
  - fast



Results(2)

- sequence of targets



- voxelize a 3D animation

Limitations

- using diffusion
  - looks not always natural
- no optimal approximation
- no very precise parameters
  - experience needed

My Opinion

- direct control
- fast
- target-driven approach is effective
- good results
- no direct control over approximation exactness

Future Work

- multi-resolution gathering term
- new and more precise control parameter
- path sketching

Discussion

?????