ANIMATING REAL-TIME FLUIDS IN COMPUTER GRAPHICS

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KEYNOTE – Infoware/Visual 2021

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BRIEF BIO

- Assistant Professor, BTH Sweden (Nov 2014 – now)
- Postdoc, INRIA Grenoble (Aug 2013 – Oct 2014)
- Research Fellow, NTU Singapore (Mar 2012 – May 2013)
- PhD, University of Zurich (July 2007 – Dec 2011)

Specialization

- Computer graphics (CG)
  - Animating fluids – water, clouds, snow
  - Processing and rendering large data sets
  - Geometric modeling
- Artificial Intelligence in use of CG
- Data science

INTRODUCTION

- Fluids ubiquitous in daily life
  - Computer games
  - Movies
  - Virtual simulations

Games - Fluids


Uncharted 4


Amnesia: Dark descent


Arkham Knight

Movies - Fluids


The Day After Tomorrow


2012


Deep Impact

INTRODUCTION

- Focus differs
  - Movies – Realism
  - Games – Efficiency

Realism Efficiency

Games - Snow

Games - Clouds

MOTIVATION

- Efficiency is very important
  - **Smart** methods, eg. Level-of-detail (LOD)
  - **GPUs** have been around for long
    - Massively parallel
  - Artificial intelligence **(AI)**
    - Learns from data

- Many simulations can be real-time now!

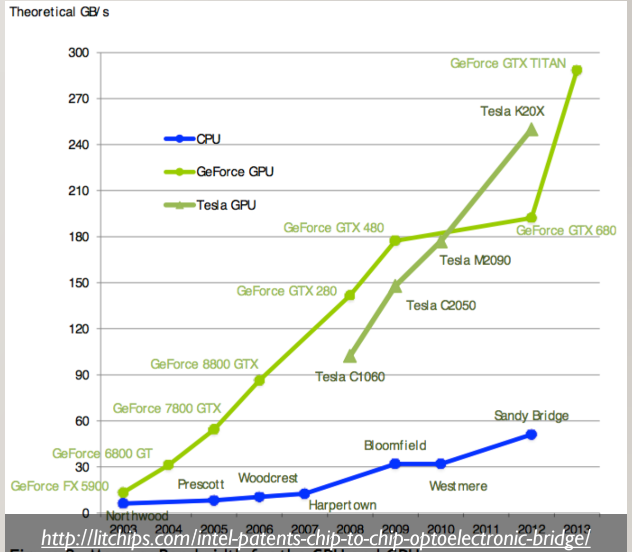
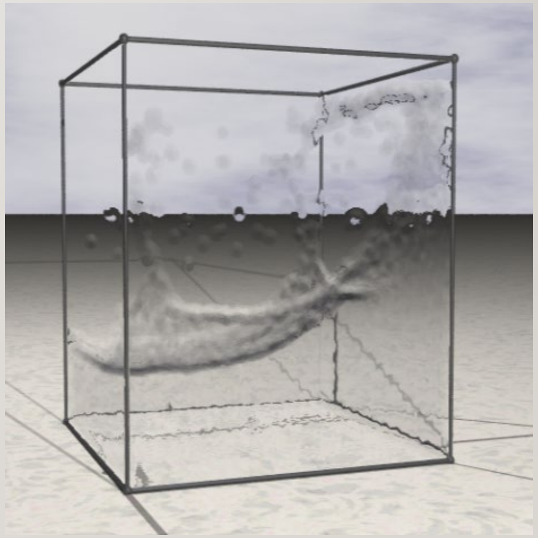


Figure 2 Memory Bandwidth for the CPU and GPU

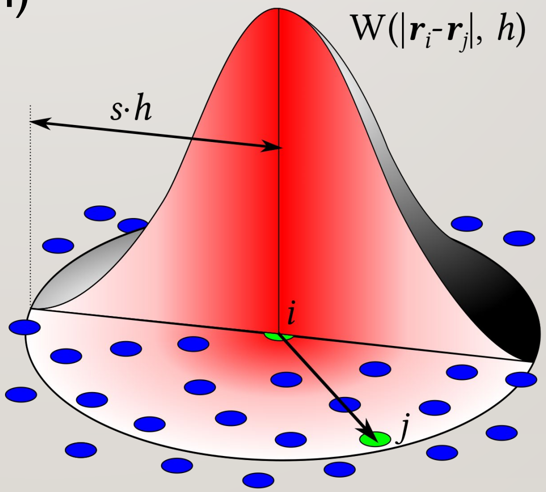
PHYSICS ANIMATION
MY INTERESTS

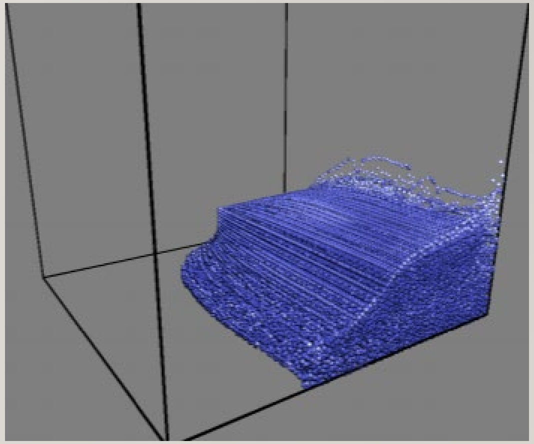
- Fluids
- Clouds
- Snow



FLUID SIMULATION

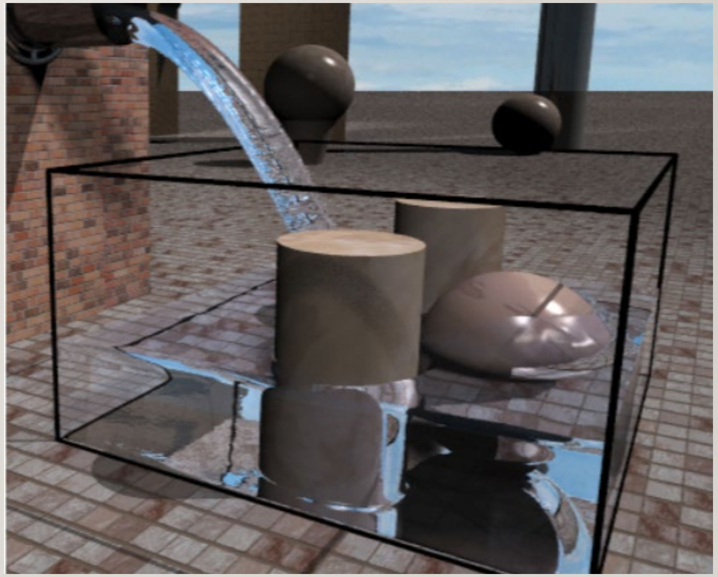
- Particle-based (Lagrangian)
  - Smoothed Particle Hydrodynamics (SPH)
  - More particles → Better simulation
  - More particles → Slower simulation
  - Need to accelerate SPH





FLUID SIMULATION
LEVEL-OF-DETAIL

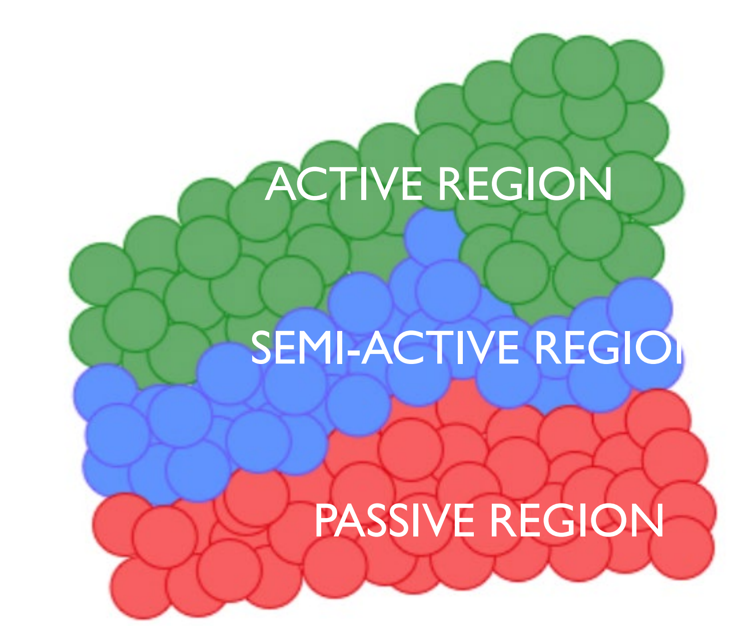
- Variable particle sizes disrupt physics
  - LOD with uniform particles
- Simulation domains have inactive regions
  - Assign different computational effort to different regions



Time Adaptive Approximate SPH, Goswami, VRIPHYS (2011)

FLUID SIMULATION
LEVEL-OF-DETAIL

- Determine various regions in the fluid simulation (every iteration)
  - Active – DO ALL PHYSICS COMPUTATIONS
  - Passive – SKIP ALL PHYSICS COMPUTATIONS
- Transition region
  - Semi-active – SOME COMPUTATIONS
- We save computation on all passive particles with low activity



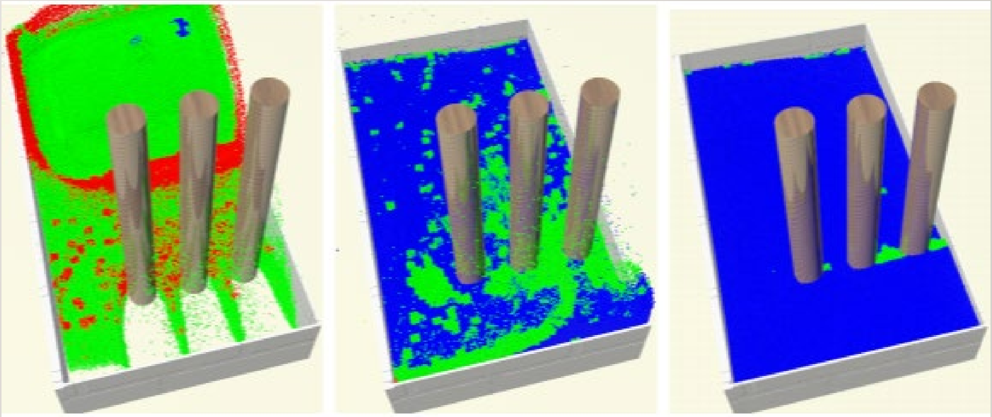
MOVIE
LEVEL-OF-DETAIL

Particles: 1 million
Speed-up: 7x

MOVIE
LEVEL-OF-DETAIL

FLUID SIMULATION
REGIONAL TIME STEPPING

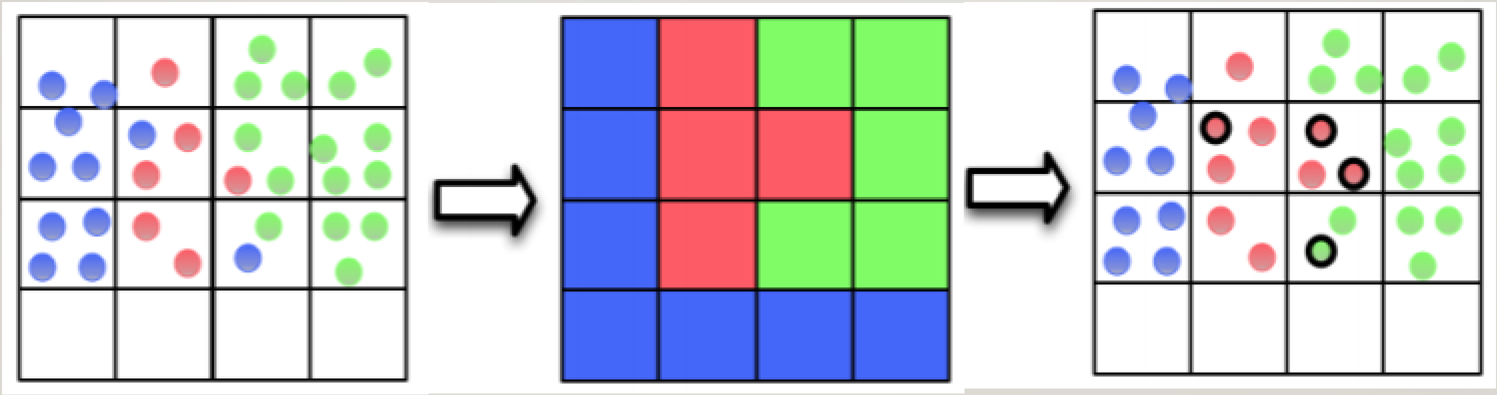
- Alternate to Freezing Particles
- Different time steps to different particles
- Based on activity
  - Fast moving particles → updated more frequently
  - Slow moving particles → updated less frequently
- No particle is ever frozen



Regional Time Stepping for SPH, Goswami & Batty, Eurographics short (2014)

FLUID SIMULATION
REGIONAL TIME STEPPING

- Block-based architecture for time step assignment
- CFL condition used



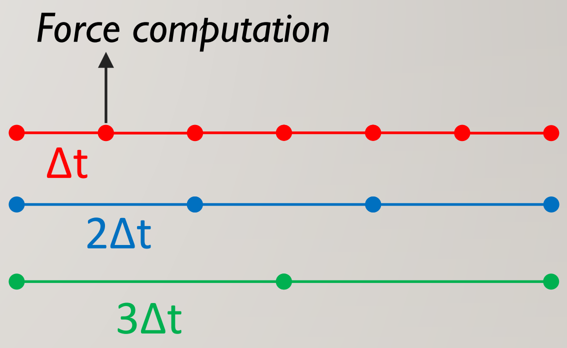
Time steps by color: Δt, 2Δt, 3Δt

FLUID SIMULATION
REGIONAL TIME STEPPING

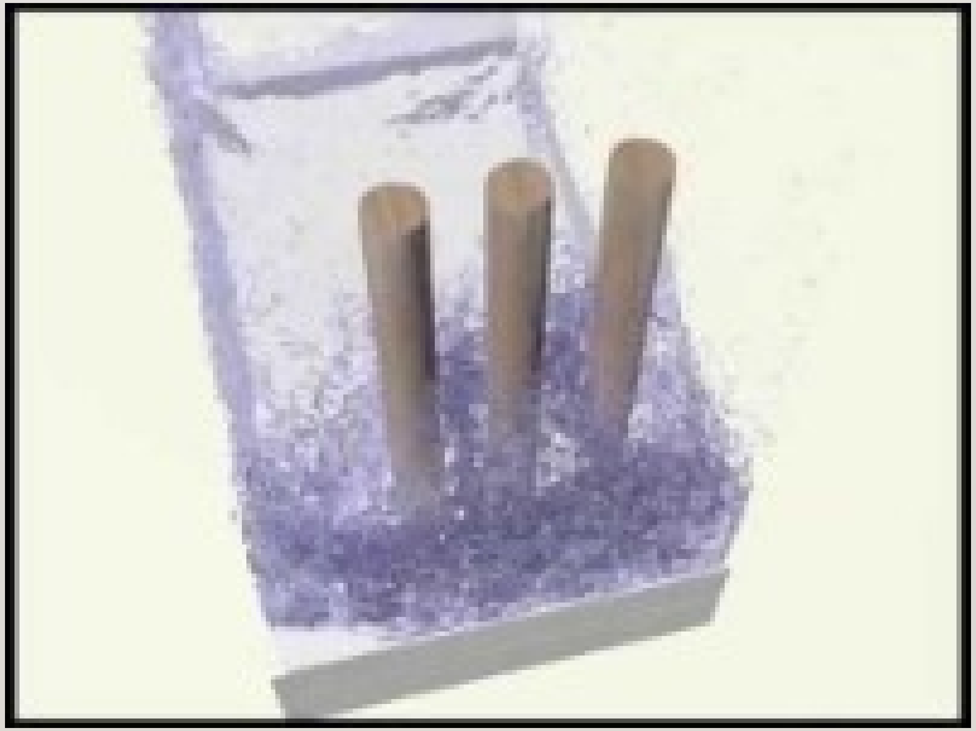
- Move each particle at every iteration
- Compute force when required (Δt, 2Δt, 3Δt)
- Apply correction

$$x_i^{n+1} = \tilde{x}_i^{n+1} + \frac{(a_i^{n+1} - a_i^n)\delta t^2}{6}$$

$$v_i^{n+1} = \tilde{v}_i^{n+1} + \frac{(a_i^{n+1} - a_i^n)\delta t}{2}$$

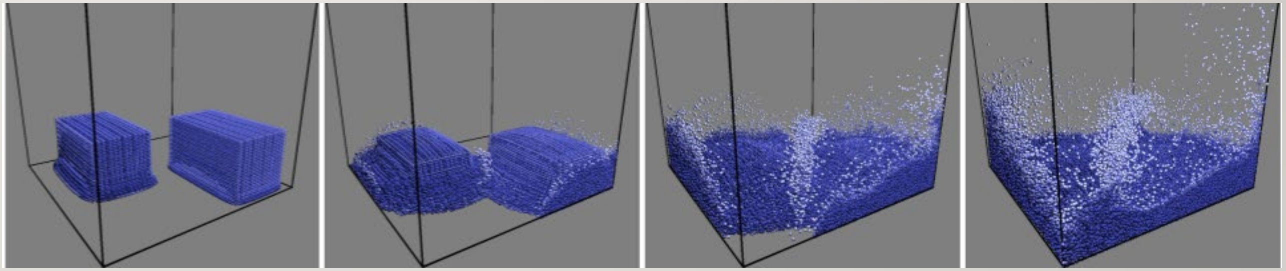


MOVIE
REGIONAL TIME STEPPING



FLUID SIMULATION
IISPH ON GPU

- Implicit Incompressible SPH
- Ported on GPU
- Nearly 6x faster than OpenMP



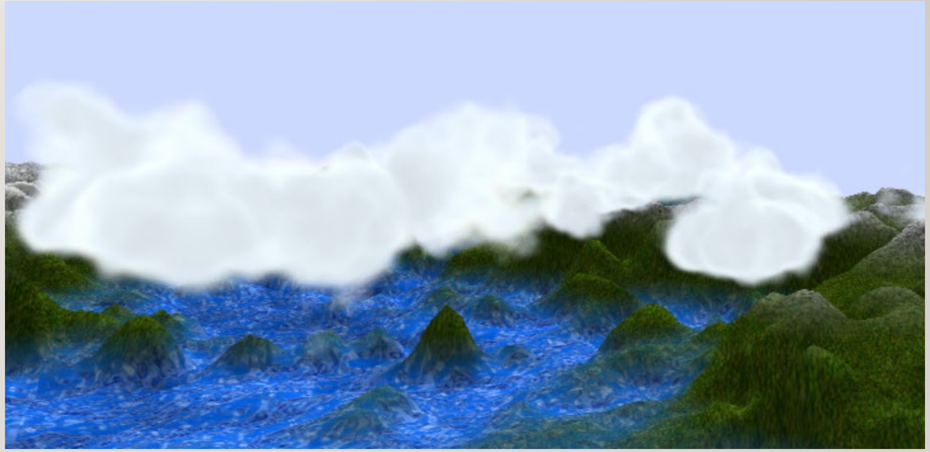
Implicit Incompressible SPH on the GPU, VRIPHYS (2015)

Particles	Physics - GPU		Physics - CPU (OpenMP)		Speedup
	Time (ms)	FPS	Time (ms)	FPS	
7 600	2.58	388	6.89	146	2.67
20 000	4.06	247	22.18	45	5.47
54 000	10.21	100	64.20	16	6.29
103 000	21.07	49	126.80	8	6.02
175 000	39.18	28	221.16	5	5.64

PHYSICS ANIMATION

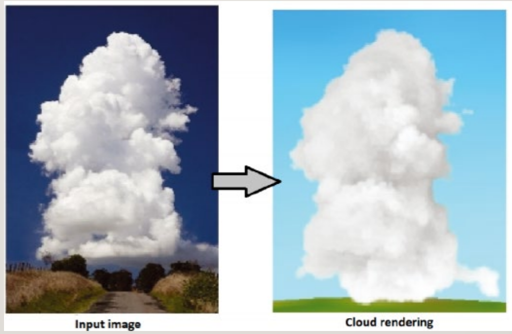
MY INTERESTS

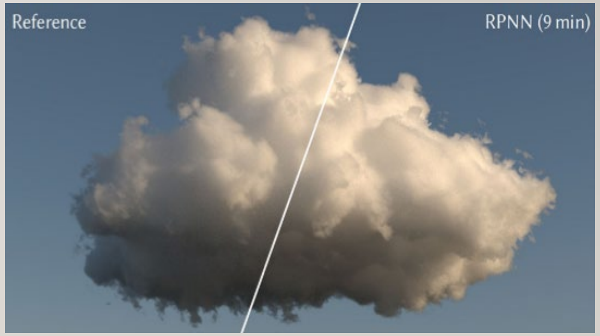
- Fluids
- Clouds
- Snow



CLOUDS

- Clouds are important in various domains
  - Atmospheric science
  - Computer graphics
- Various steps involved
  - Modeling
  - Rendering
  - Animation





A survey of modeling, rendering and animation of clouds in computer graphics, Goswami, Visual Computer, 2020

CLOUDS

- Cloud **animation** challenging
  - Detailed data storage
    - Cloud, surrounding air
  - Detailed computations
- Real-time performance was out of question!
  - Landscape-scale

About 500K-1M particles simulated on GPU
Barbosa et al. 2015

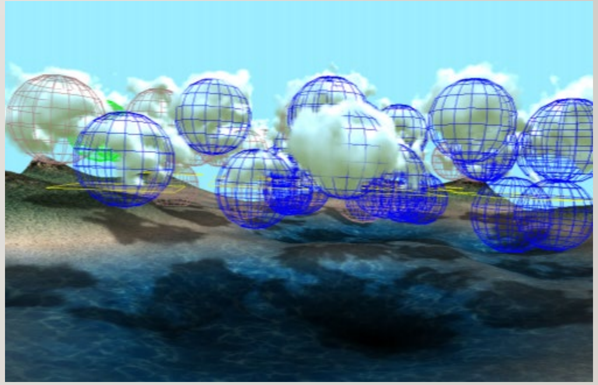
CLOUDS
PHYSICS + PROCEDURALISM

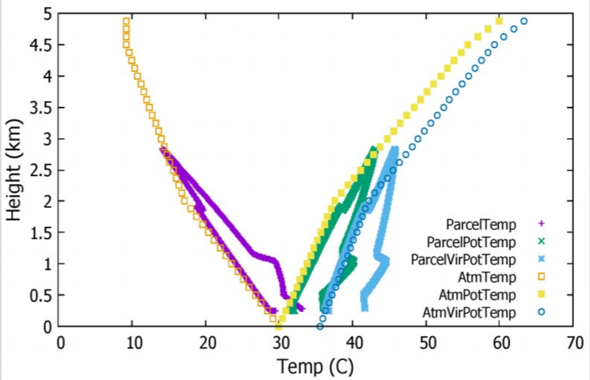
- We proposed a hybrid model
  - Expensive Physics → Macro level
  - Rendering → Micro level
- Rendering is controlled using physics
- Particle-based approach
- Operates at interactive frame rates

Real-time landscape-size convective clouds simulation and rendering, Goswami & Neyret, VRIPHYS, 2017

CLOUDS
PHYSICS + PROCEDURALISM

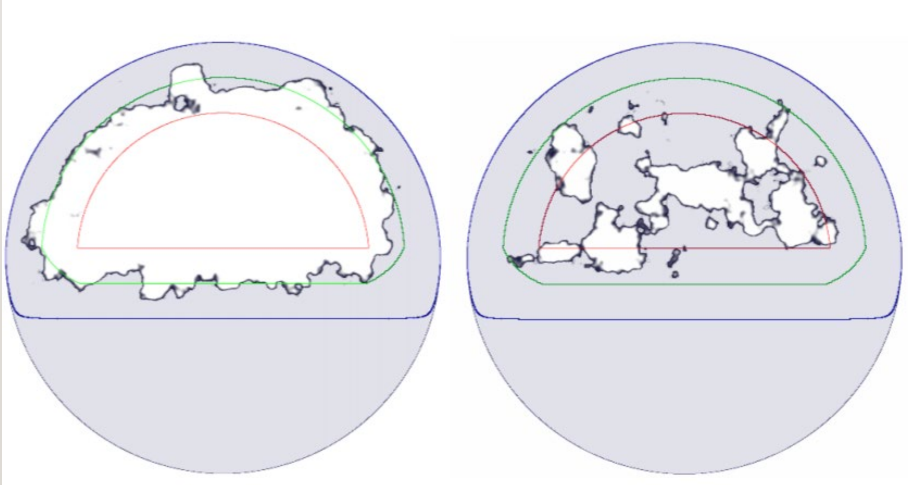
- Macro physics units parcels
- Implicit environment
  - Temperature with height
  - Humidity with height
- Forces on parcel
  - Gravity, bouyancy, air drag, atmospheric, SPH
- Mixing with environment
  - Entrainment, detrainment
- **Physics inexpensive -- computed on CPU**



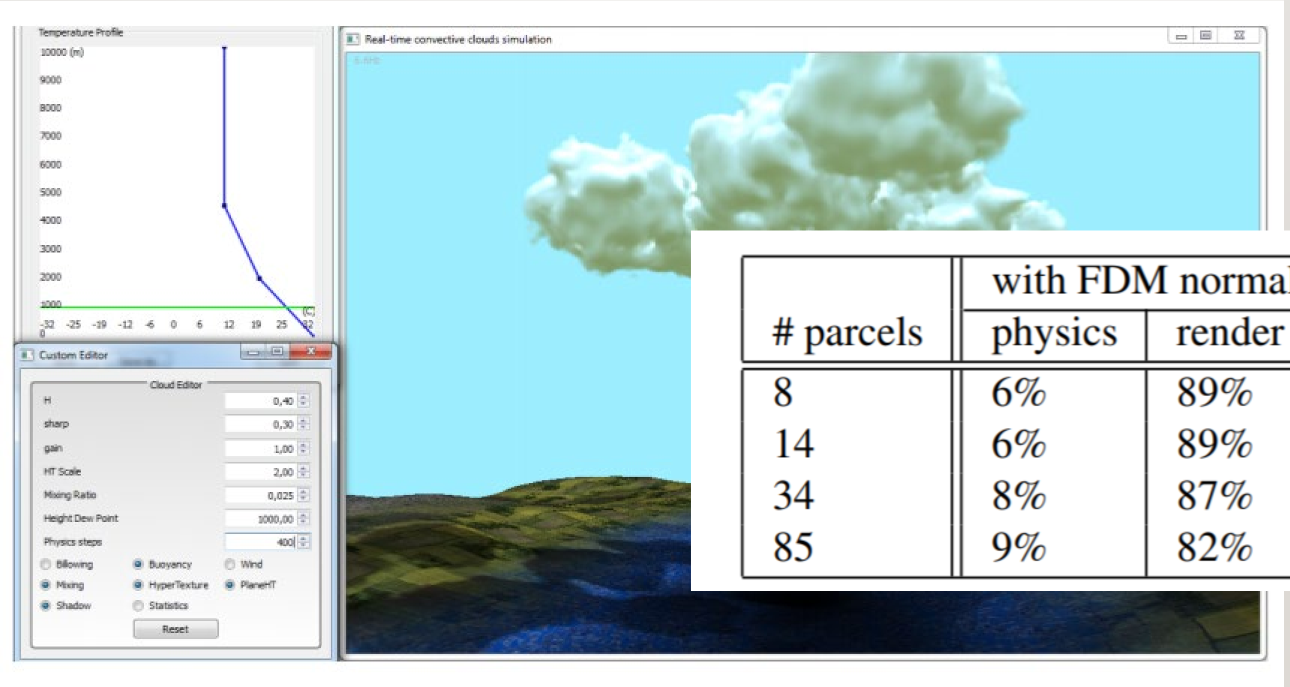


CLOUDS
PHYSICS + PROCEDURALISM

- Output from physics
  - Condensed fraction of water in each parcel (η)
- Visualization
  - Hypertexture dependent on η



CLOUDS
PHYSICS + PROCEDURALISM



# parcels	with FDM normals			without FDM normals		
	physics	render	fps	physics	render	fps
8	6%	89%	128	4%	78%	235
14	6%	89%	77	6%	91%	160
34	8%	87%	24	8%	89%	63
85	9%	82%	7	9%	88%	21

CLOUDS
MOVIE

Less than 100 parcels

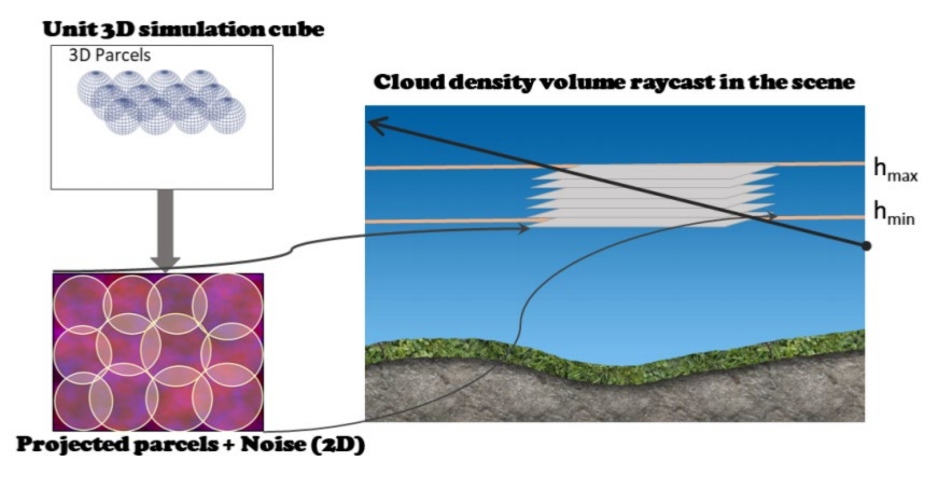
CLOUDS
CLOUD MAP

- Improvement to previous method
- With increasing number of parcels
    - Parcel physics grows expensive
    - Hypertexture generation becomes exponentially expensive
- Limited cloud shapes
- New method reduces parcel count significantly
- We still keep our hybrid approach of *physics controlled proceduralism*

Interactive animation of single-layer cumulus clouds using cloud map, Goswami, STAG, 2019

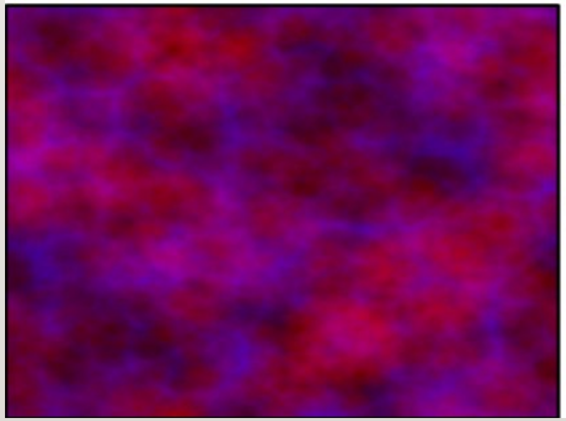
CLOUDS
CLOUD MAP

- Obtain physics profile from a few parcels
- Project them onto a plane
- Use this planar texture to generate hypertexture

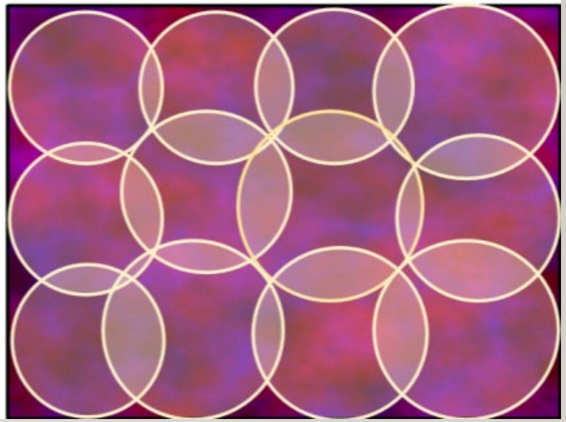


CLOUDS
CLOUD MAP

- 16 parcels employed
- Superimposing *Physics profile* on *Noise profile*
- Highly saves on
  - Sphere-ray intersection tests while generating hypertexture
  - Physics when using many parcels
- Allows better cloud shapes



Noise profile



Noise + Physics profile

CLOUDS
CLOUD MAP

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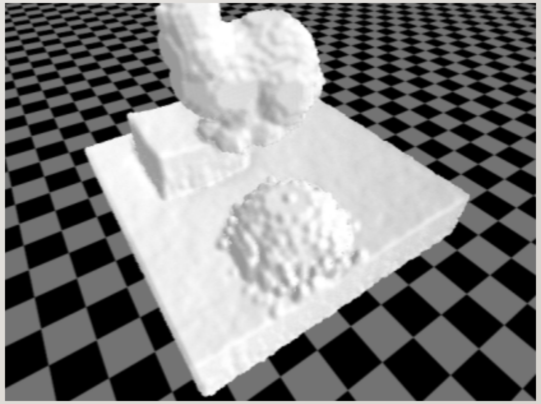
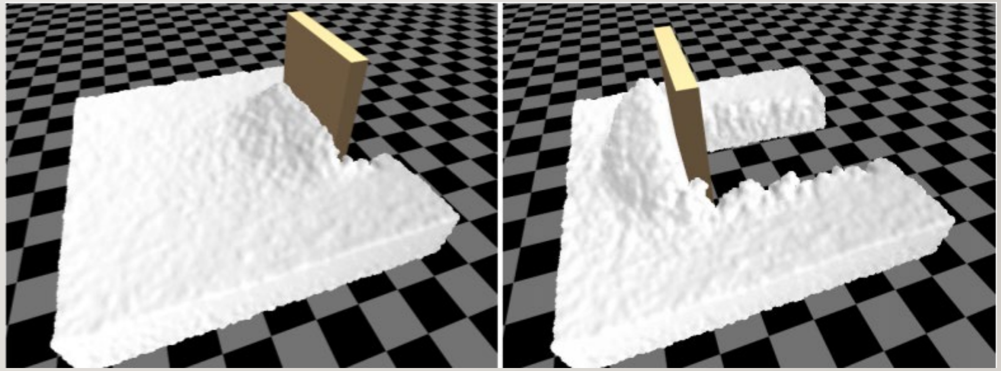


SNOW

- My recent research interest
- Snow animation highly challenging
  - Complex physics
  - Various states (solid, powder, …)
  - Bonds
  - Effect of temperature
- No prior real-time solution existed

SNOW

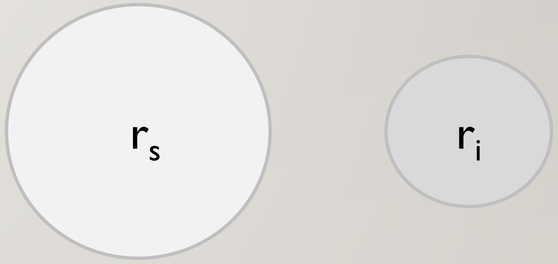
- Purely particle-based approach
- GPU-based
- Supports both animation and rendering in real times
  - Relatively large particle counts



Real-time particle-based snow simulation on the GPU, Goswami et al., EGPGV, 2019

SNOW

- Discretize snow into particles
  - Snow (r_s), Ice (r_i)
- Assign state to each particle based on radius
  - $\eta \rightarrow$ snow ratio, $(1-\eta) \rightarrow$ ice ratio
  - Interpolate properties
    - $E = E_s * \eta + E_i * (1 - \eta)$



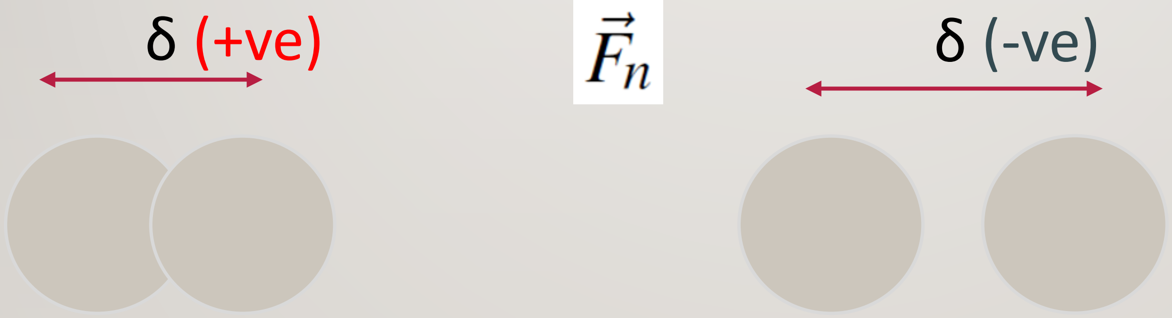
Density :

$\rho_s \rightarrow 100 - 800\ kg/m^3$

$\rho_i \rightarrow 800 - 900\ kg/m^3$

SNOW
FORCES

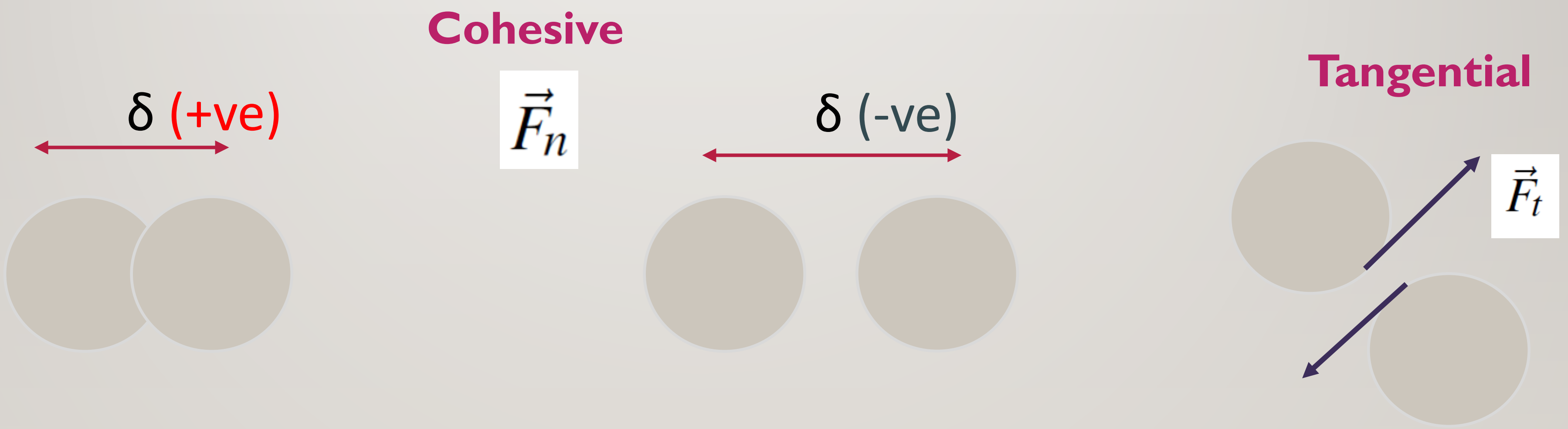
Cohesive



HagenMuller et al. 2015

$$\vec{F}_n = \begin{cases} -\frac{E_j r_j + E_k r_k}{2}\delta\vec{n} & \text{if } -\frac{E_j r_j + E_k r_k}{2}\delta < 4\frac{\sigma_{nj} r_j^2 + \sigma_{nk} r_k^2}{2} \\ 0 \text{ and cohesion is broken,} & \text{otherwise} \end{cases}$$

SNOW
FORCES



HagenMuller et al. 2015

SNOW
BONDS

- Bonds crucial to capture correct snow behavior
- Particles with broken bond do not enter cohesion
- Memory intensive – expensive
- We introduce an approximation
  - Set a threshold on $\frac{n_{curr}}{n_{max}}$

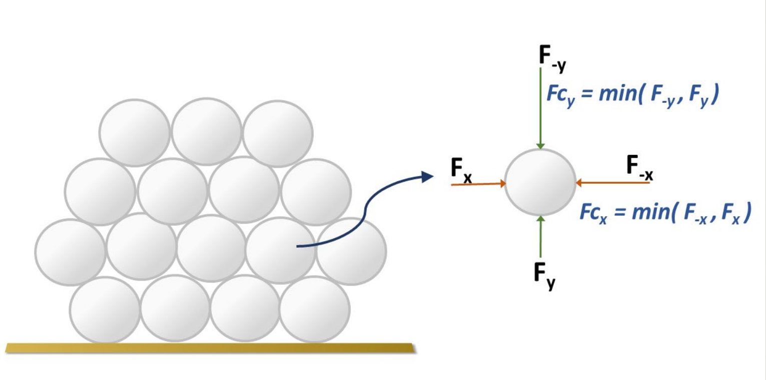
No bonds broken **Bonds broken**

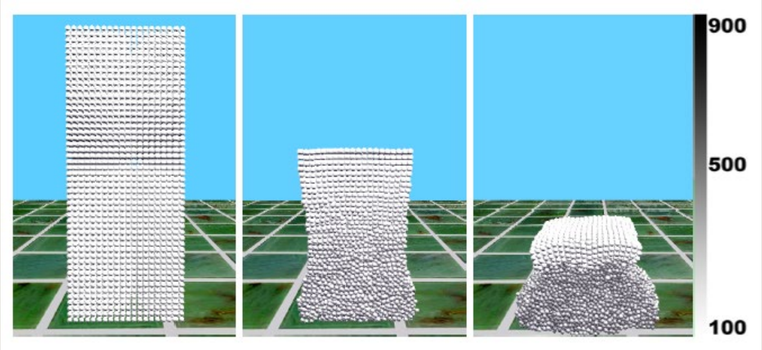
SNOW
COMPRESSION

- Compression caused due to opposing forces
- Durability (d)
  - To account for trapped air

$$d \leftarrow \begin{cases} d - k_q p_c, & \text{if } \vec{F}_c > \vec{D}(\rho_i) \\ d & \text{otherwise} \end{cases}$$

- Boundary particles mirror force





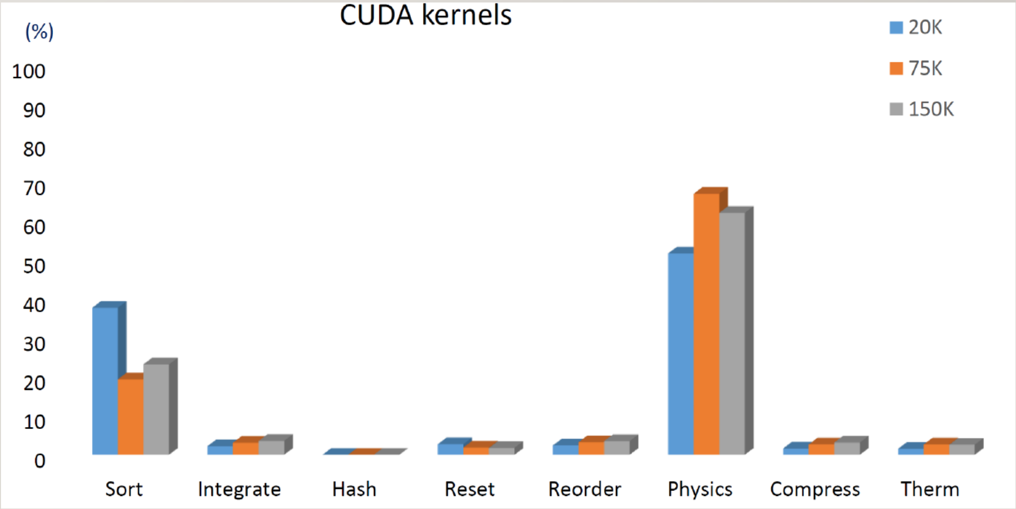
SNOW
RESULTS

- CUDA, C++
- Some parameters modified

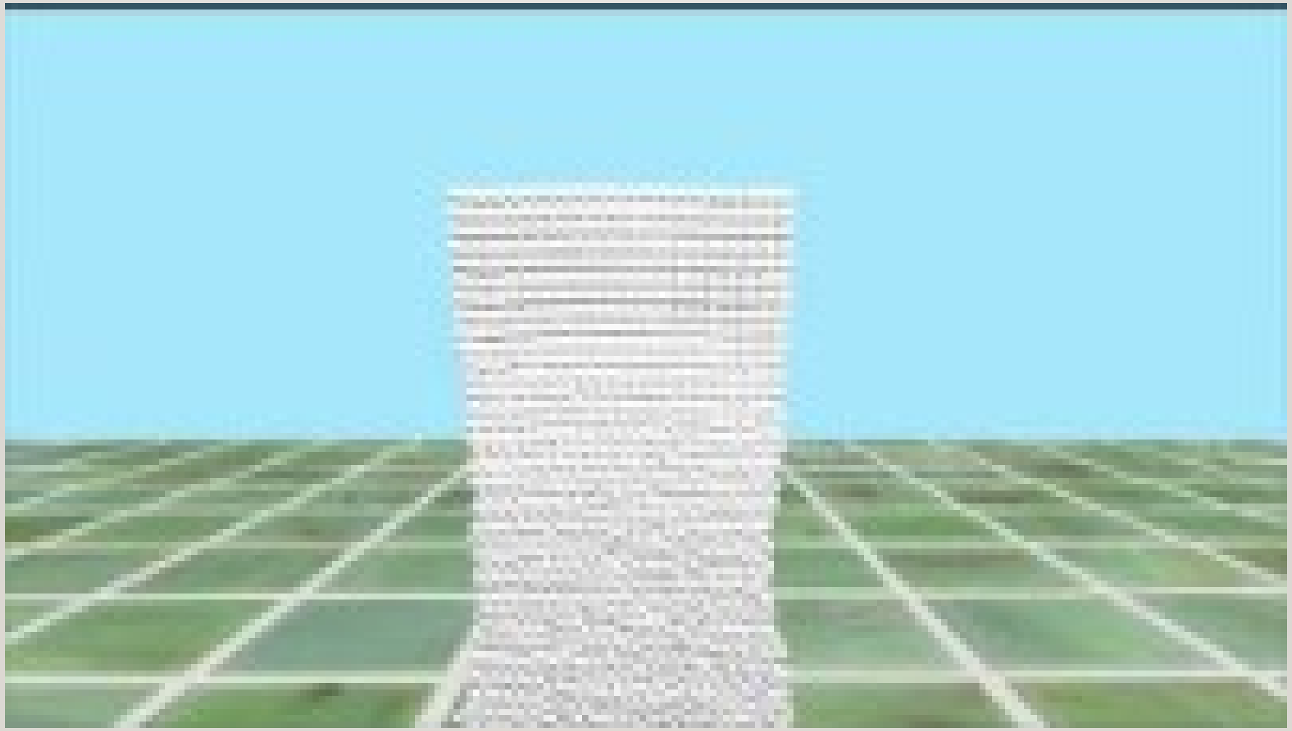
E_{snow}	Young modulus snow 100 kg/m^3	5000 Nm^{-2}
E_{ice}	Young modulus ice 900 kg/m^3	35000 Nm^{-2}
φ	Angle of repose	$38°$

Frame rates

Particle count	Rendering-**surface**	Rendering-**particles**
8000	734	1023
20000	580	783
35937	430	607
75615	282	335
111000	230	268



SNOW
MOVIE



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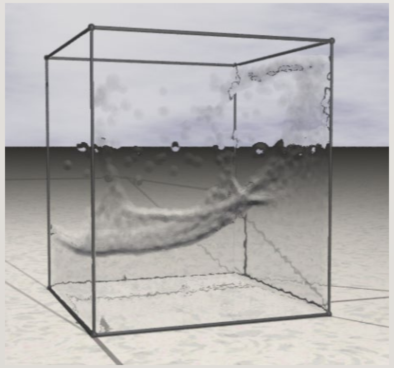
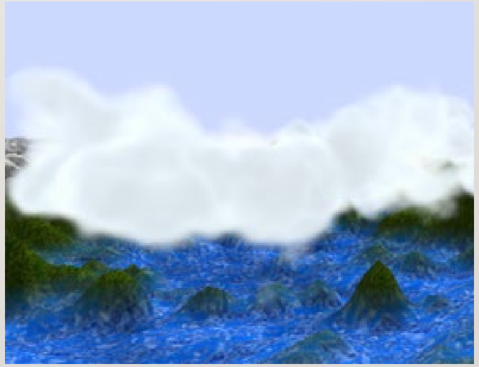
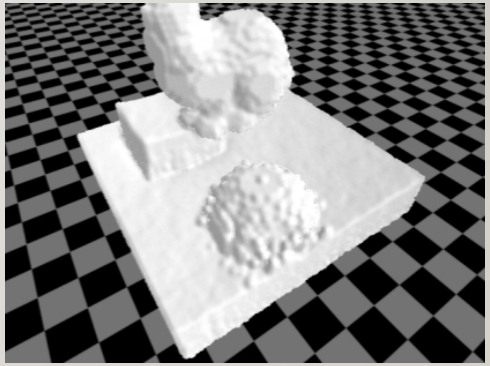


THANK YOU