Extending OpenSees for the Particle Finite Element Method

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Outline

1. Motivation
2. Particle Finite Element Method
   - Introduction to PFEM
   - Basic Equations
   - Fractional Step Method (FSM)
3. Implementation in OpenSees
   - Problems of the implementation of FSM
   - Options and solution to the implementation of FSM
   - Example
   - Mesh and Remesh
4. Sensitivity Analysis of PFEM
   - Introduction to the sensitivity
   - Computing sensitivity
   - Example

Fluid-Structure Interaction

- Recent natural disasters
- Simulating structural response to wave loading

OSU's Hinsdale Wave Research Lab (www.flickr.com/photos/scottfrey)

- Computational challenges
- The "OpenSees" homophone

Introduction to PFEM

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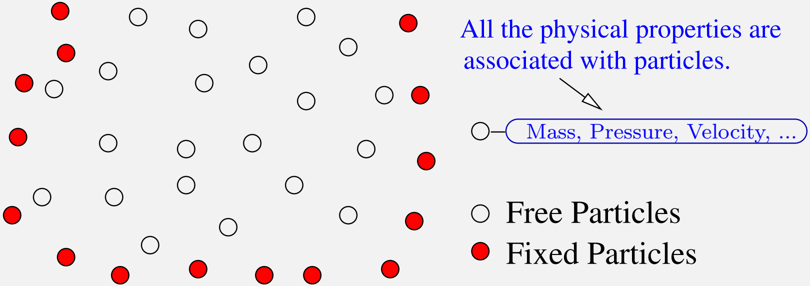

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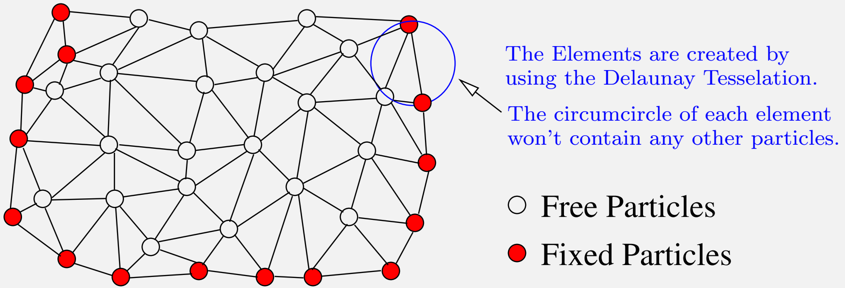

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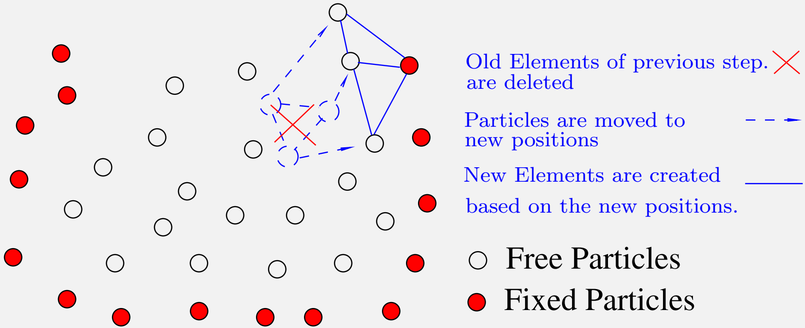

Basic Equations

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- Conservation Laws

Mass:

$$\frac{D\rho}{Dt} + \rho\frac{\partial u_i}{\partial x_i} = 0$$

Momentum:

$$\rho\frac{Du_i}{Dt} = -\frac{\partial}{\partial x_i}P + \frac{\partial}{\partial x_j}\sigma_{ij} + \rho f_i$$

Where,

ρ – Density, u_i – Velocities

x_i – Coordinates, P – Pressure

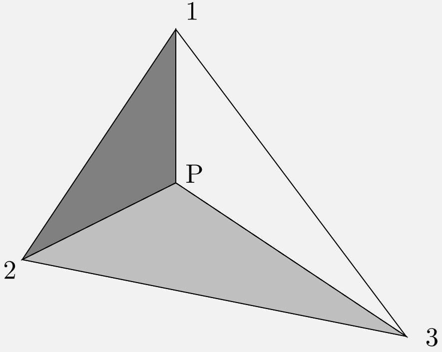
σ_{ij} – Cauchy Stress, f_i – Body forces

Basic Equations

- Linear interpolation (Unstable for incompressible continuum)

$$N_i = L_i \qquad i = 1, 2, 3 \text{ For 2D}$$

Where, N_i is the shape function, L_i is the area coordinate for node i



For point P, the area coordinates

$$L_1 = \frac{areaP23}{area123}$$

$$L_2 = \frac{areaP13}{area123}$$

$$L_3 = \frac{areaP12}{area123}$$

Basic Equations

- Discretized equations (stabilized by Finite Calculus Method)

$$\mathbf{M}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} = \mathbf{F}$$

where,

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$$\mathbf{F} = \begin{bmatrix} \bar{\mathbf{F}} & \mathbf{0} & \mathbf{0} \end{bmatrix}^T$$

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$$\dot{\mathbf{U}} = \begin{bmatrix} \dot{\mathbf{v}} & \dot{\mathbf{p}} \end{bmatrix}^T$$

$\bar{\mathbf{M}}$ – Mass matrix

$\bar{\mathbf{K}}$ – Stiffness matrix

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Blue matrices are related to the stability issues of incompressible fluid.

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To overcome this problem, the fractional step method (FSM) is used to solve the discretized equations.

Fractional Step Method (FSM)

- Predictor of velocity $\mathbf{v}^*$

$$\mathbf{v}^* = \mathbf{v}^n - \Delta t \bar{\mathbf{M}}^{-1} \left[\bar{\mathbf{K}} \mathbf{v}^j - \mathbf{G} \mathbf{p}^j - \mathbf{f} \right]$$

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- Pressure increment $\delta \mathbf{p}$

$$\delta \mathbf{p} = -(\mathbf{L} + \Delta t \mathbf{S})^{-1} \left[\mathbf{G}^T \mathbf{v}^* + \mathbf{Q} \boldsymbol{\pi}^j + \mathbf{L} \mathbf{p}^j \right]$$

where,

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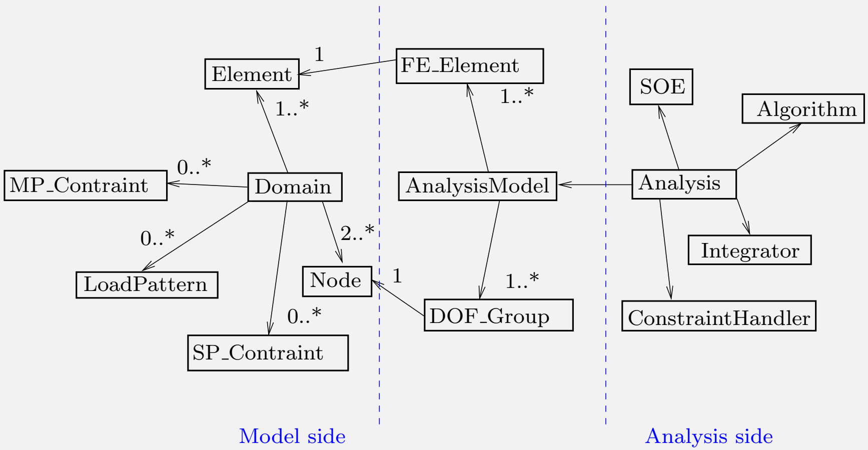
- Pressure gradient $\boldsymbol{\pi}^{j+1}$

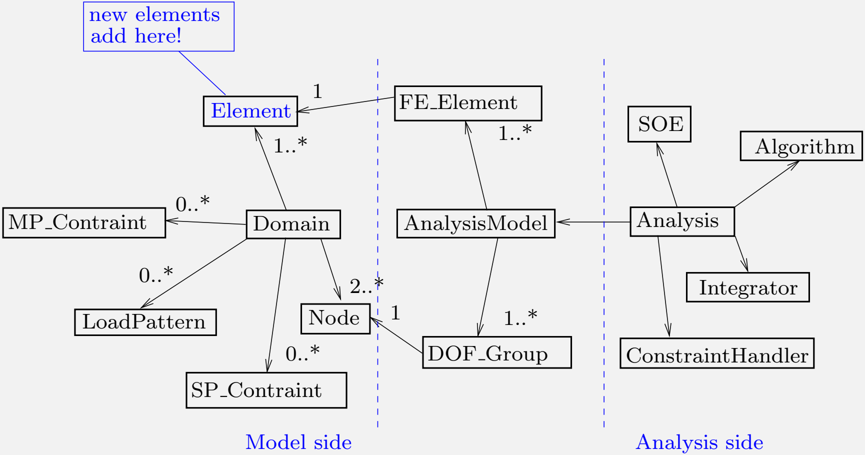
$$\boldsymbol{\pi}^{j+1} = -\hat{\mathbf{M}}^{-1} \mathbf{Q}^T \mathbf{p}^{j+1}$$

Outline

OpenSees class diagram



Flow of assembling local matrices to global



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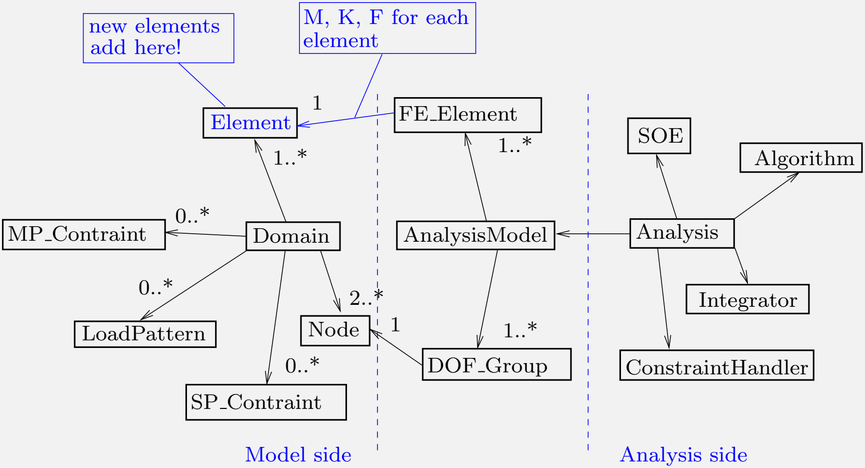

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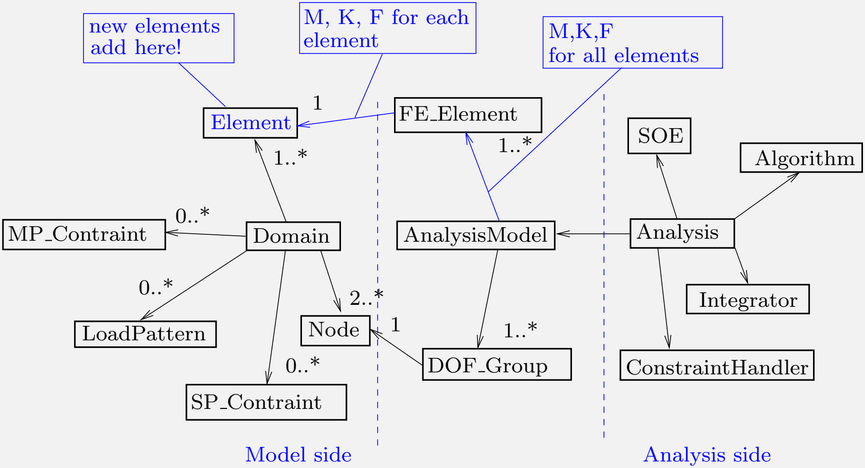

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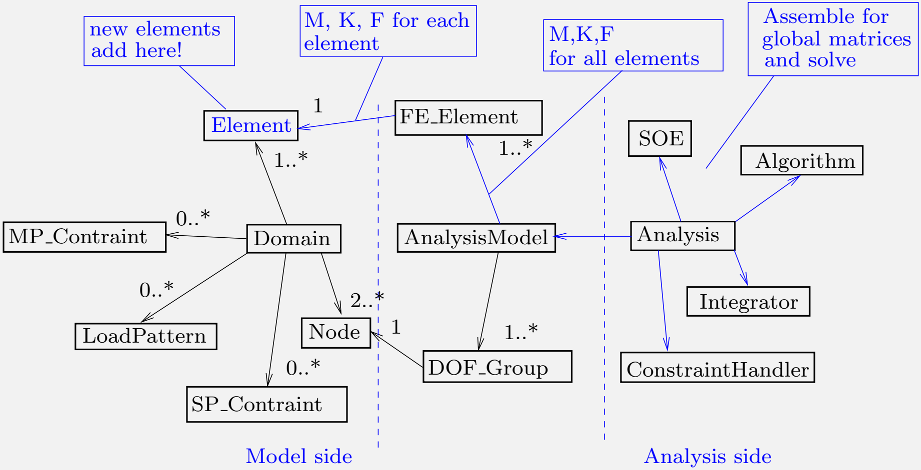

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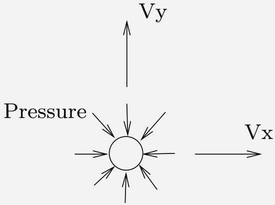
- From the flow chart shown before, global matrices are only available in the analysis side. So we can only partition matrices in the analysis side.

Problems of the implementation of FSM

- FSM is strongly related to the model. It assumes each node has 3 DOFs, vx, vy and pressure. Any implementation of FSM is coupled to the model information.



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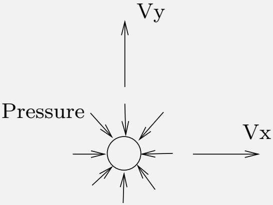

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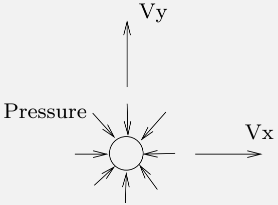

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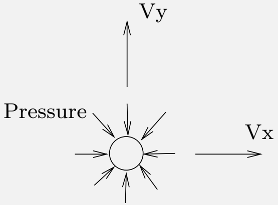

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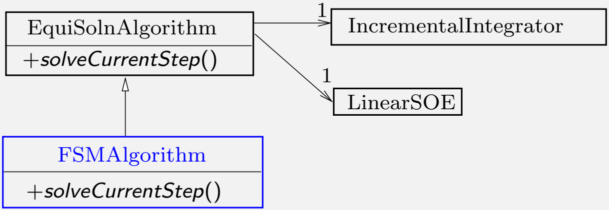

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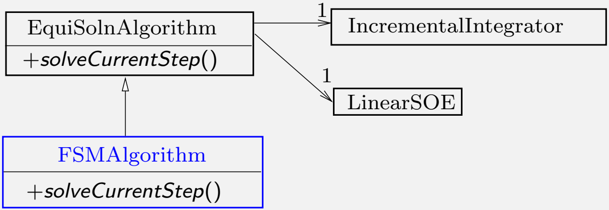

We want use `FSMAlgorithm` to partition matrices in the global level. But `FSMAlgorithm` does not have the DOFs information. To get the information, another new class `PFEMIntegrator` has to be added also.

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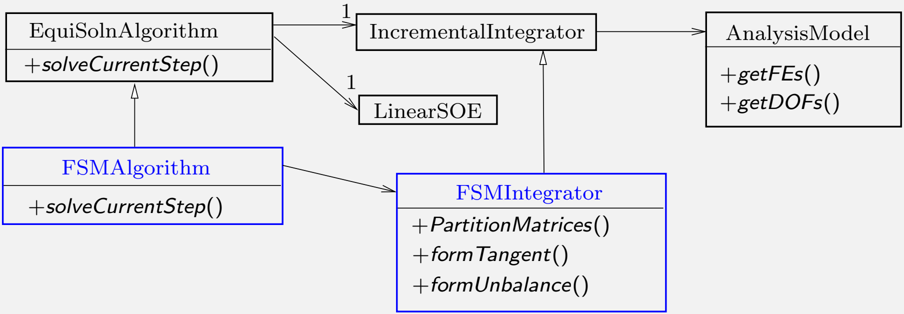

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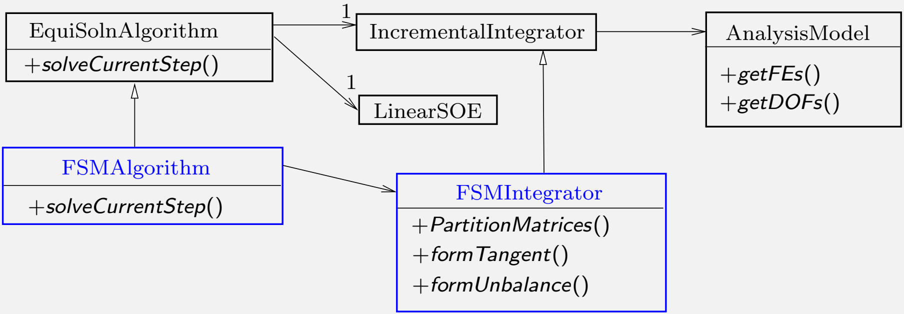

However, this implementation makes the algorithm and integrator too specialized for FSM and needs new methods in the interface of the FSM algorithm and integrator. The FSM algorithm and integrator are coupled to the model information.

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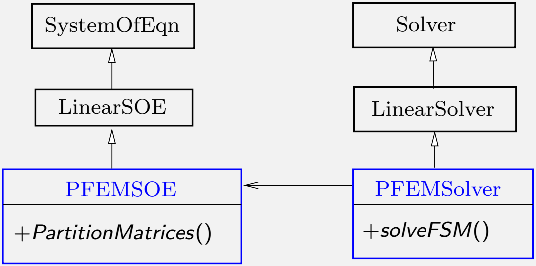

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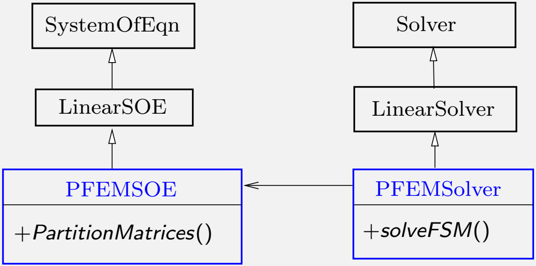

This option has the same problem with option 1 that neither `LinearSOE` nor `Solver` knows the DOFs information. They cannot partition without knowing IDs and only work with each other.

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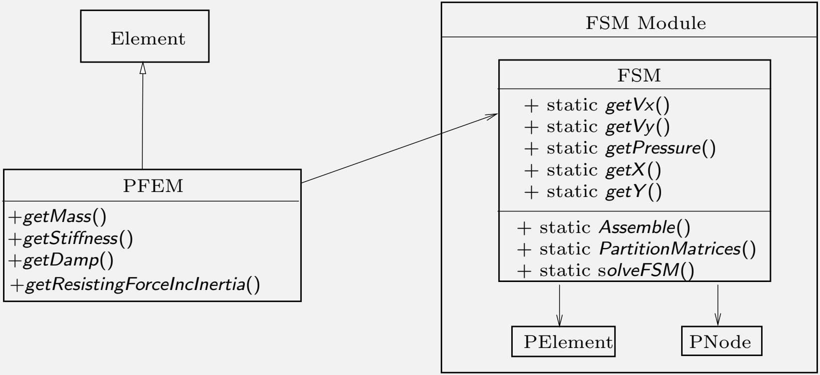

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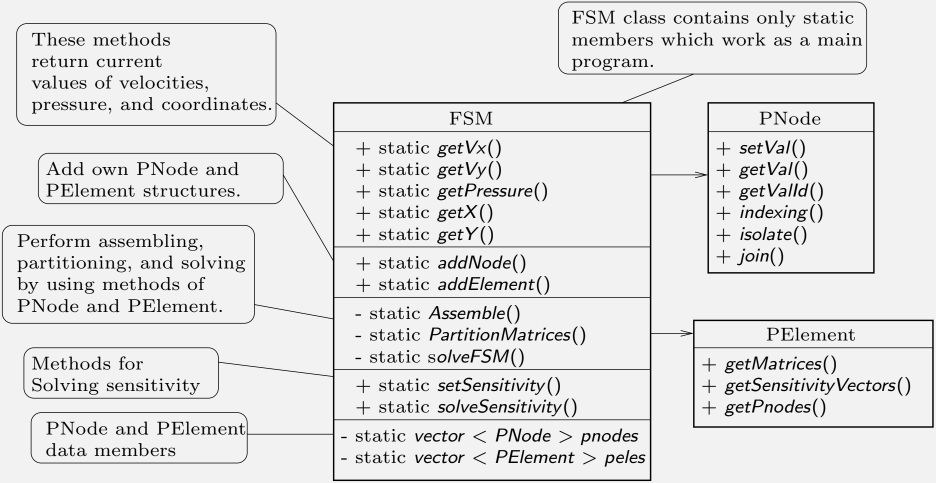

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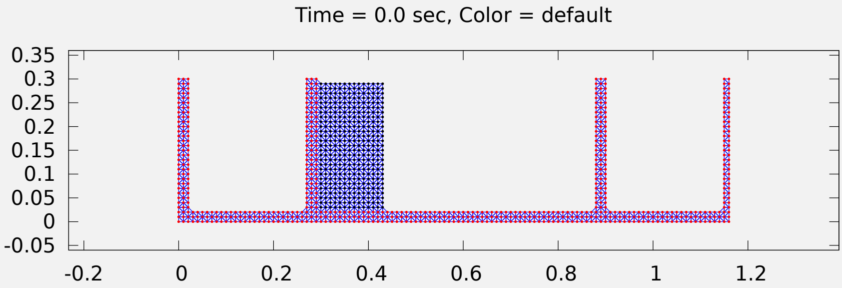
- Pressures are hidden from OpenSees. `PFEM` elements can be treated uniformly as solid elements in OpenSees.
- `PNode` and `PElement` are standalone structures used by `FSM` for storing its nodes and elements

Water column collapse

- A standard test problem of PFEM, involving large domain changing and strong nonlinearity.
- A water column is kept in a container by an unseen vertical board. Start by removing the board.



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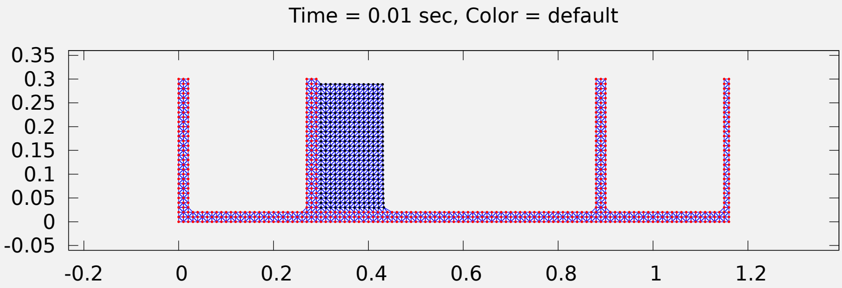

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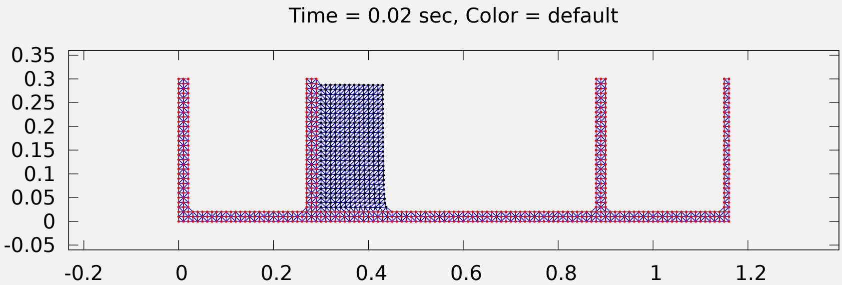

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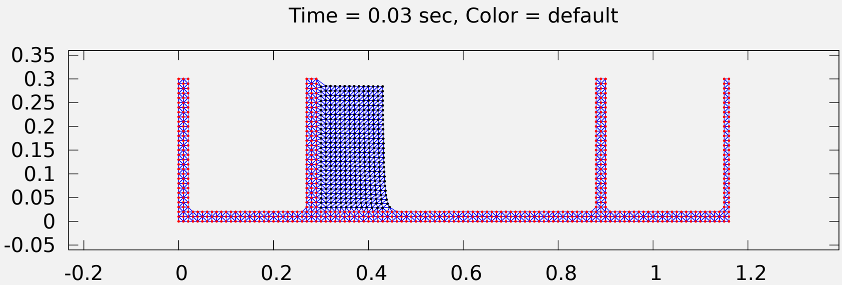

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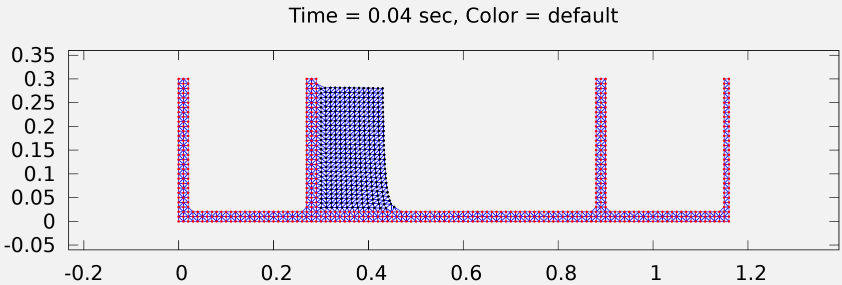
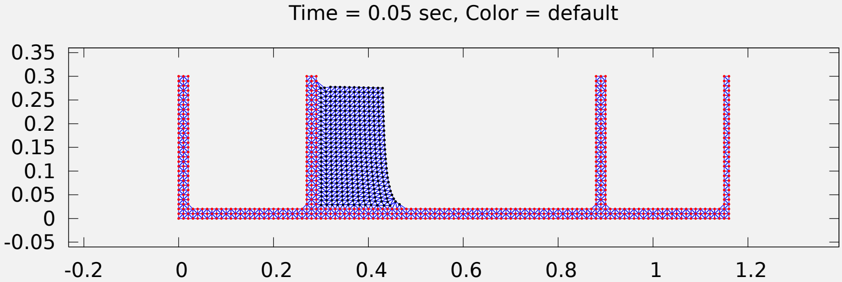


Water column collapse



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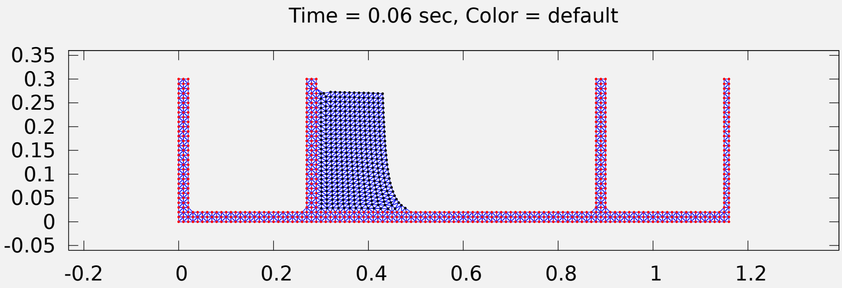

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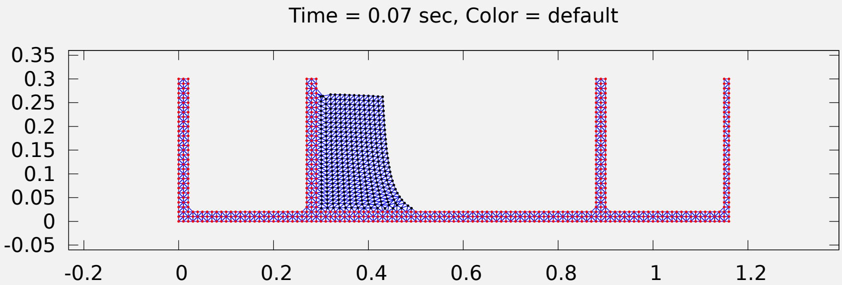

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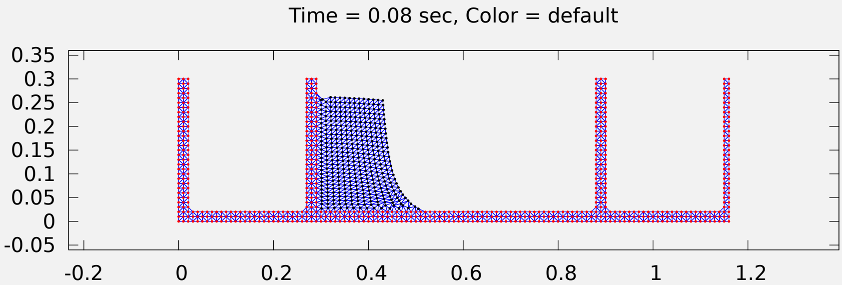

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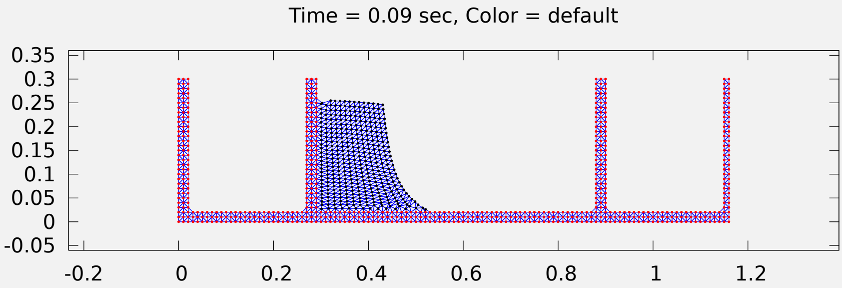

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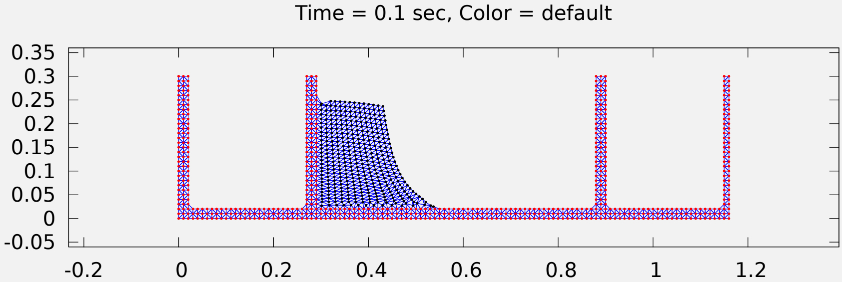

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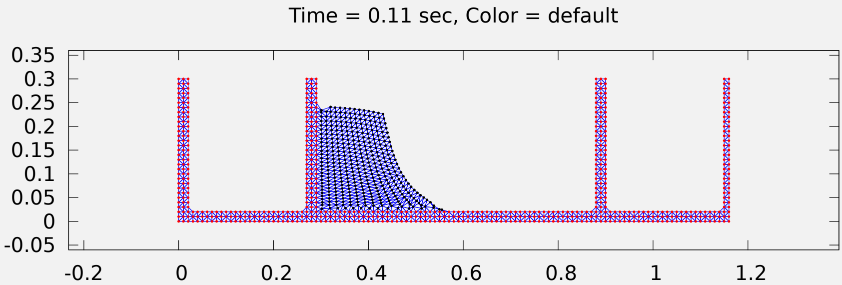

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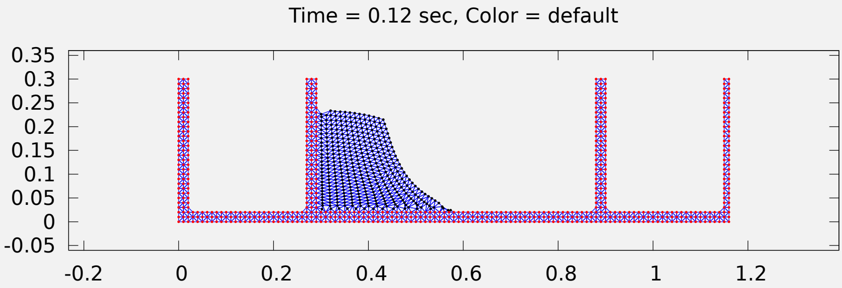

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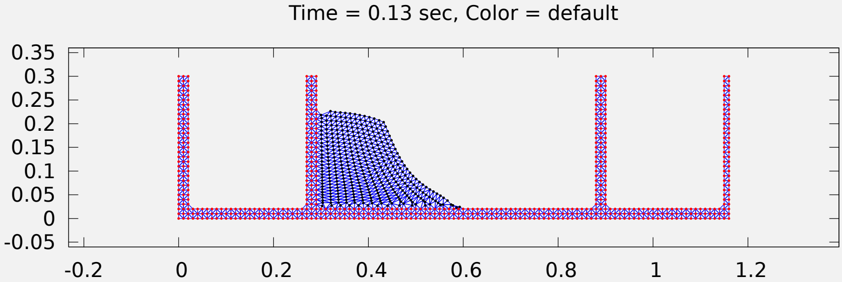

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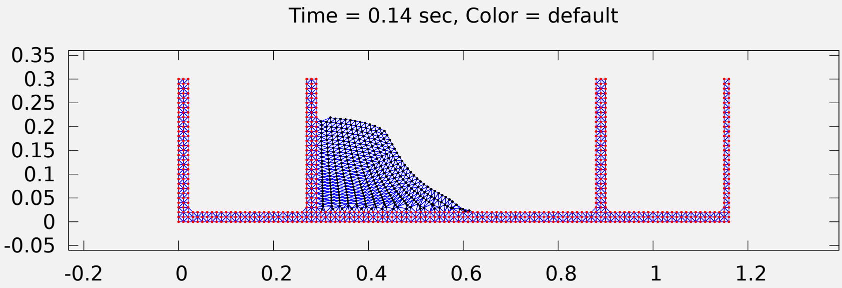

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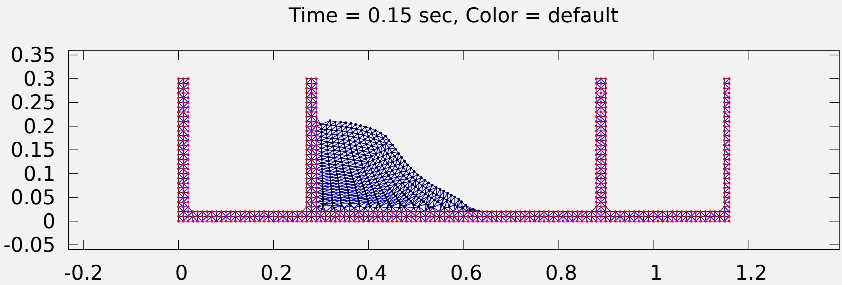

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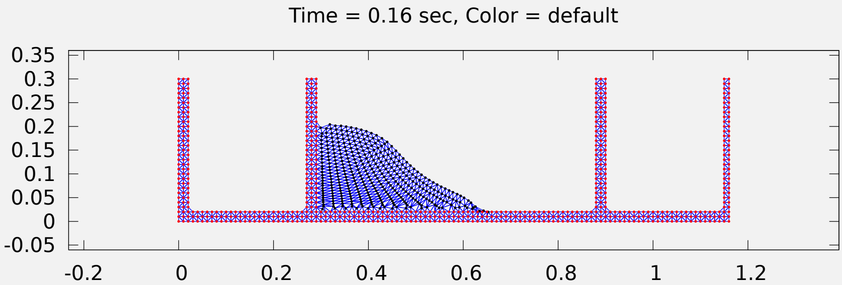

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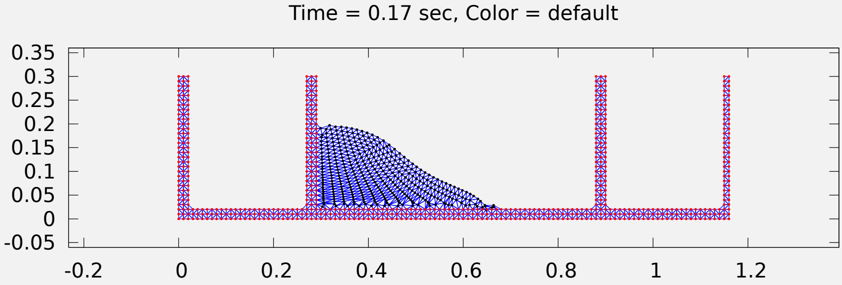

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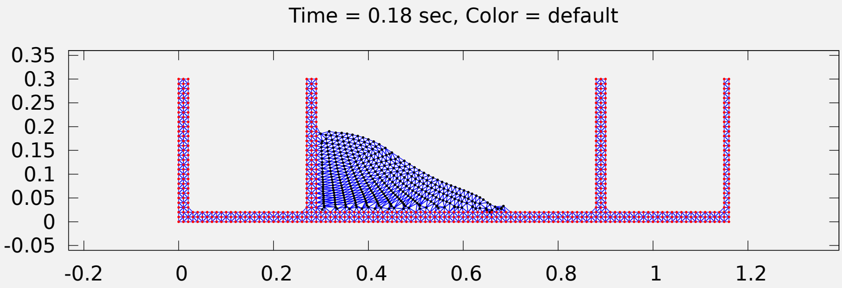

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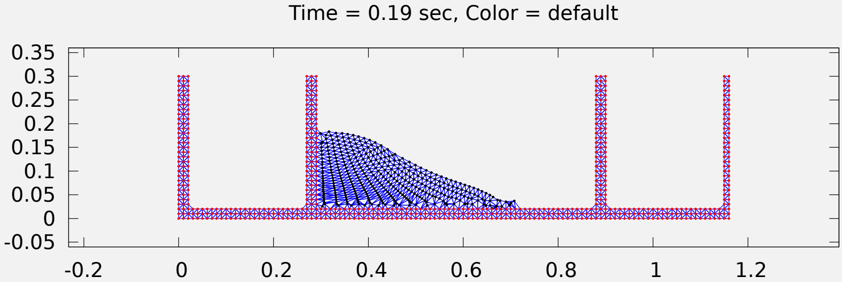

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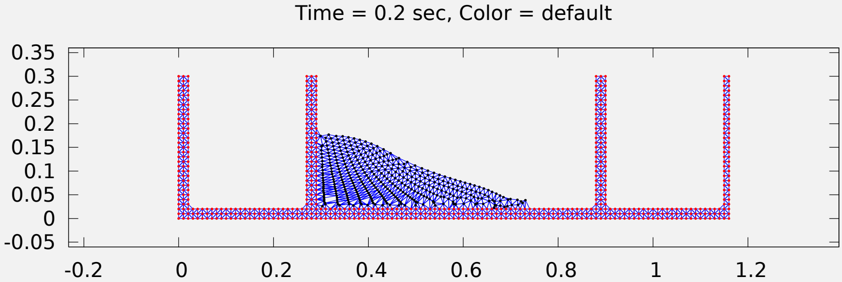

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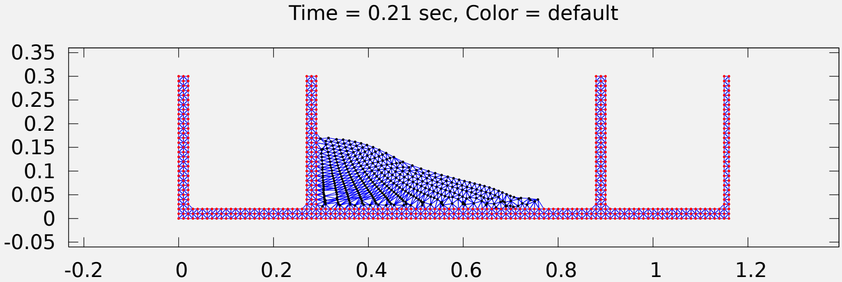

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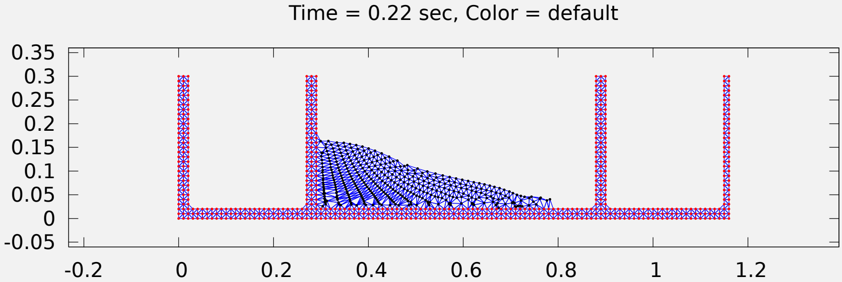

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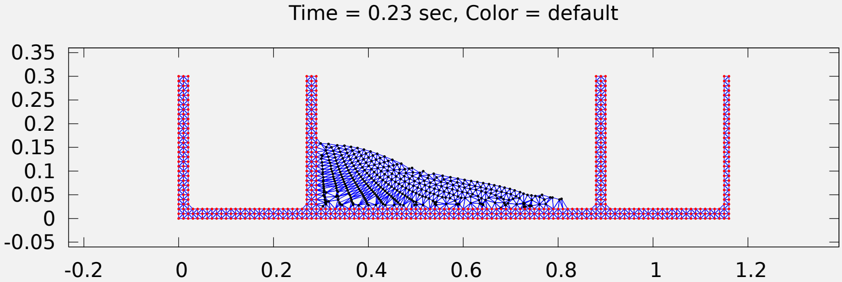

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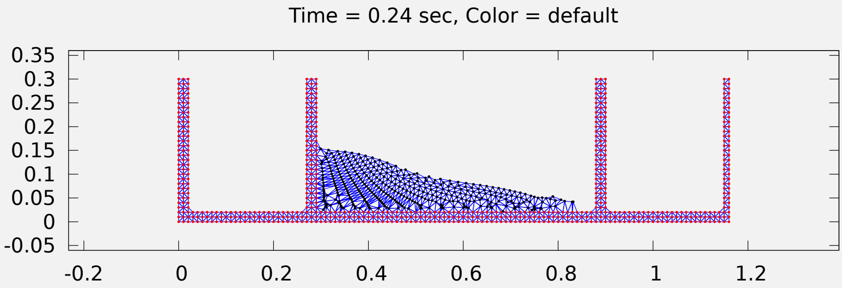

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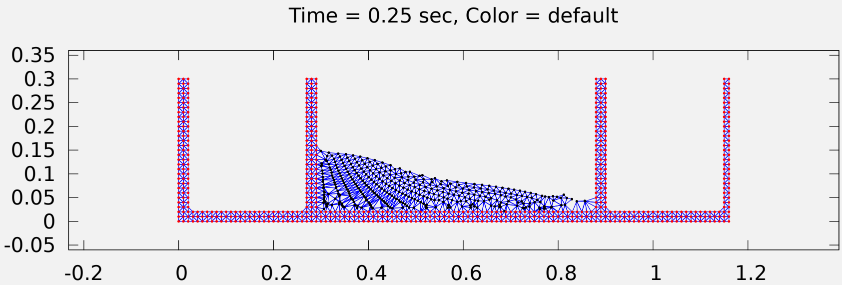

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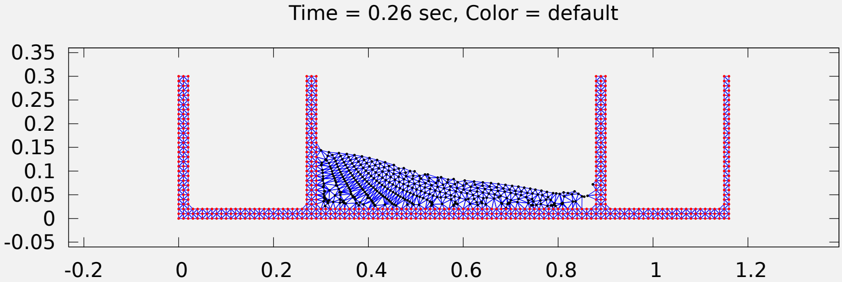

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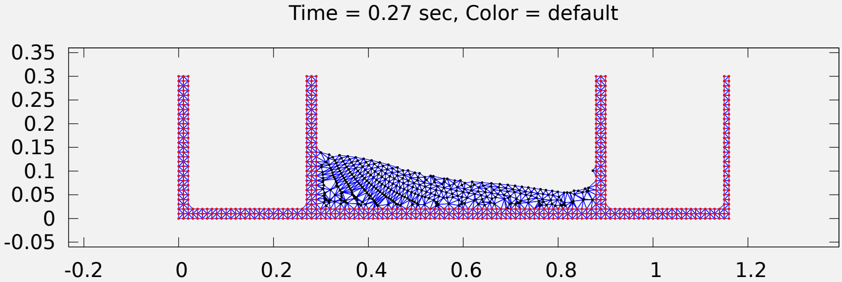

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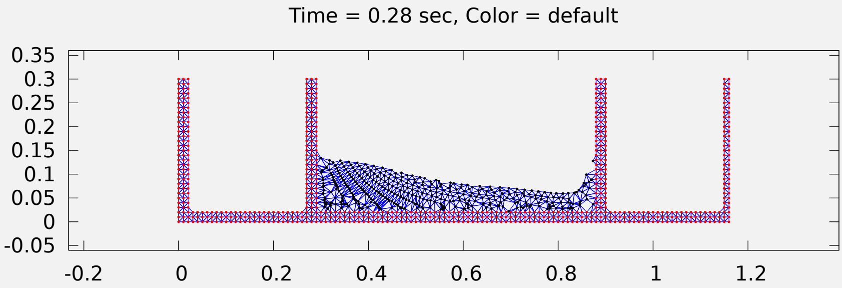

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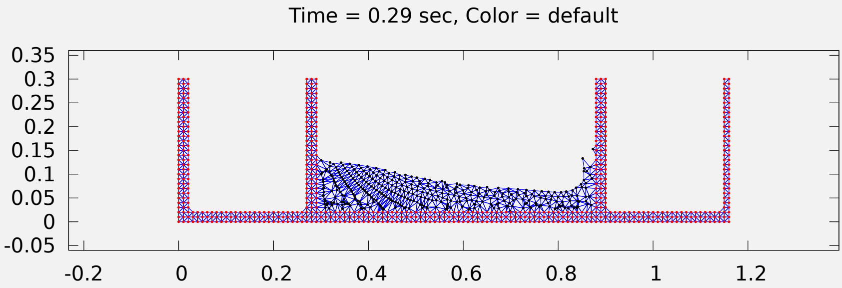

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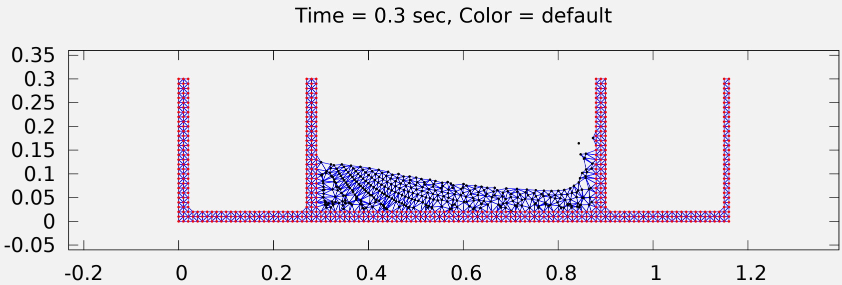

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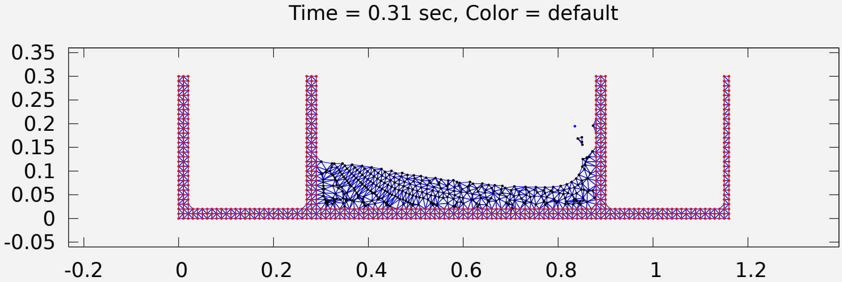

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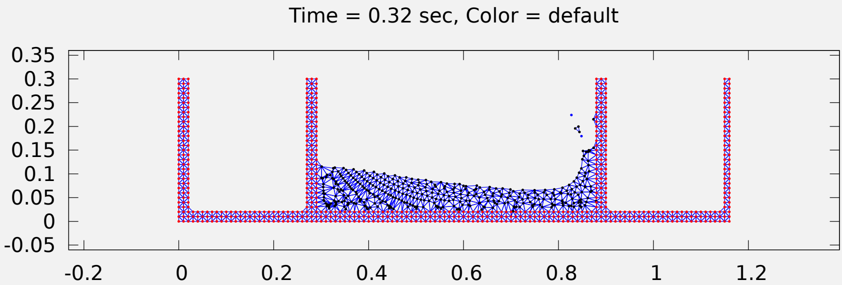

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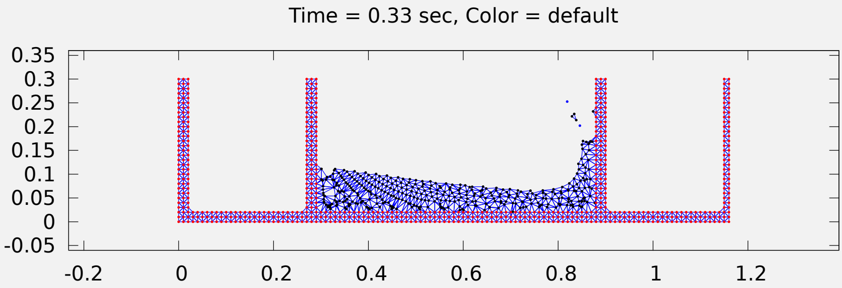

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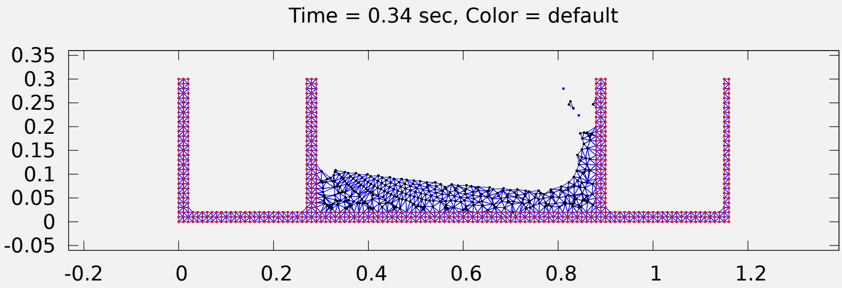

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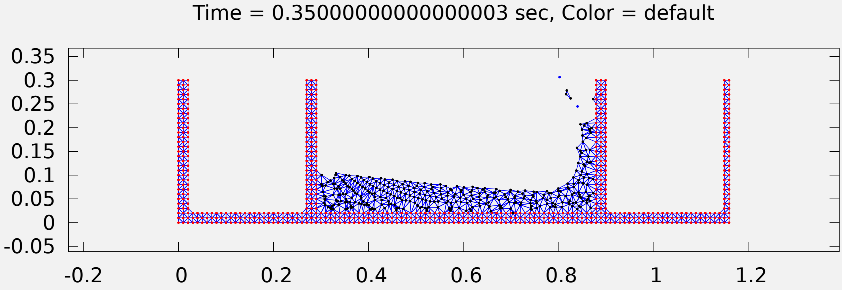

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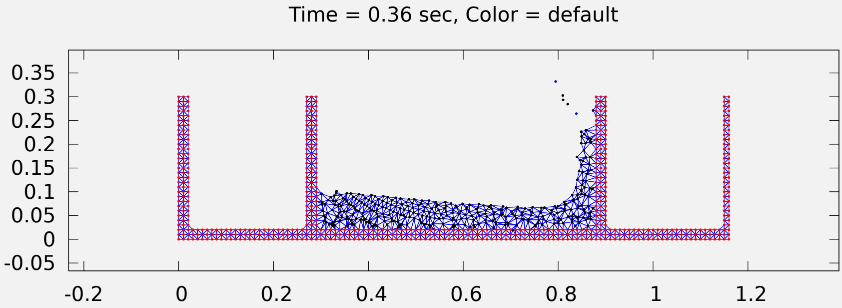

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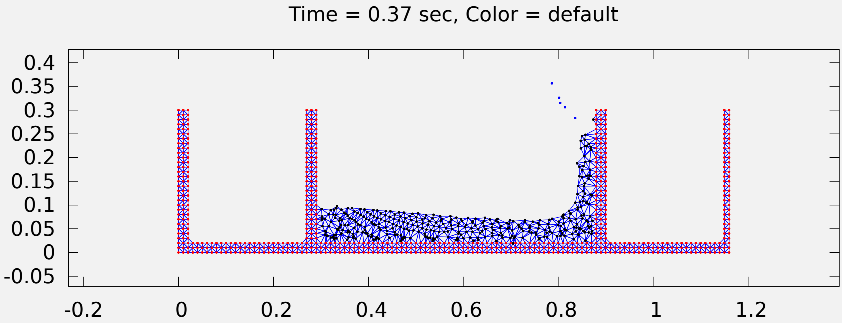

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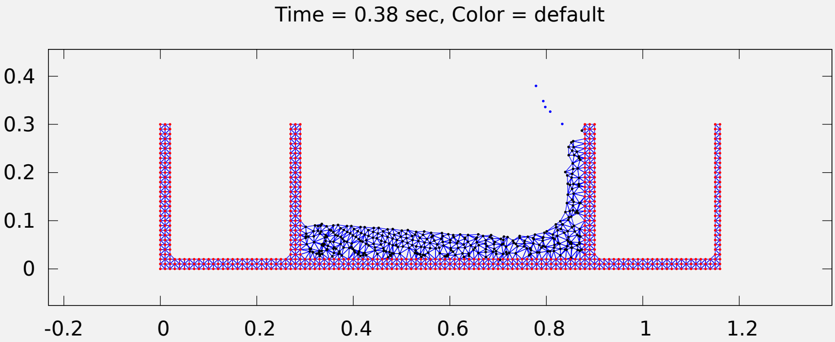

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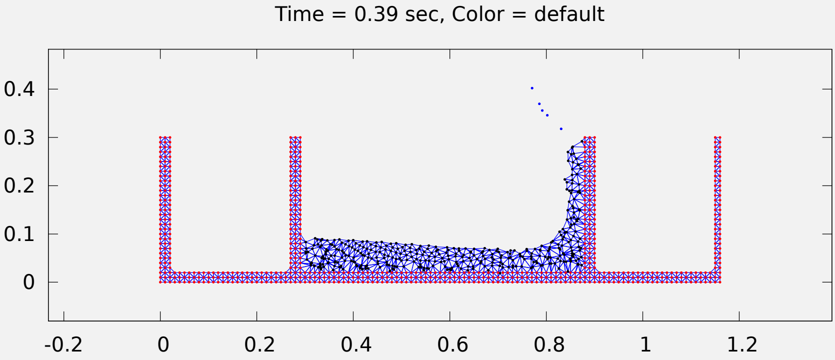

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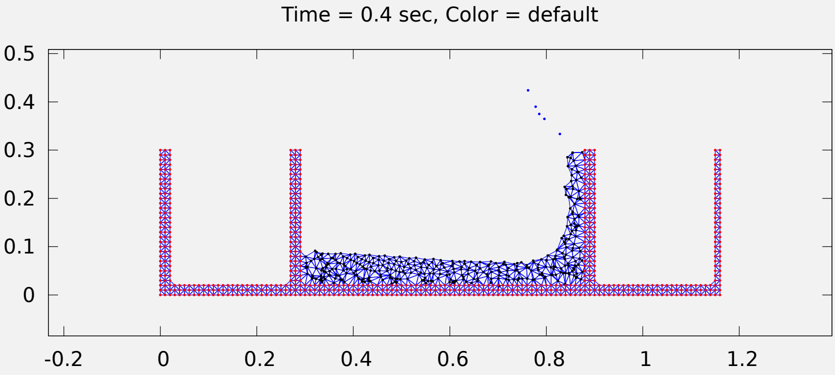

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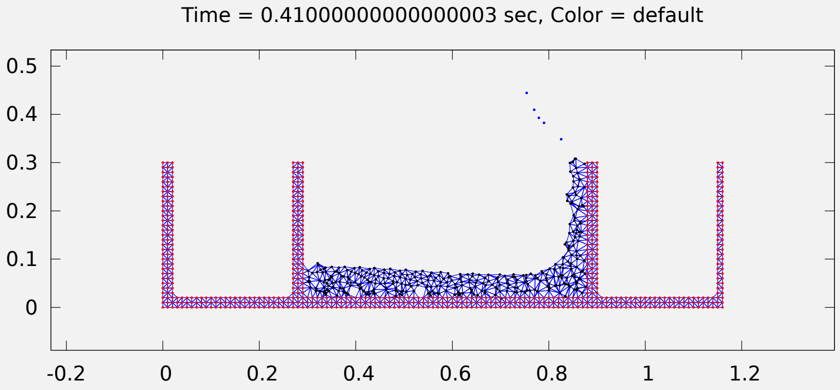

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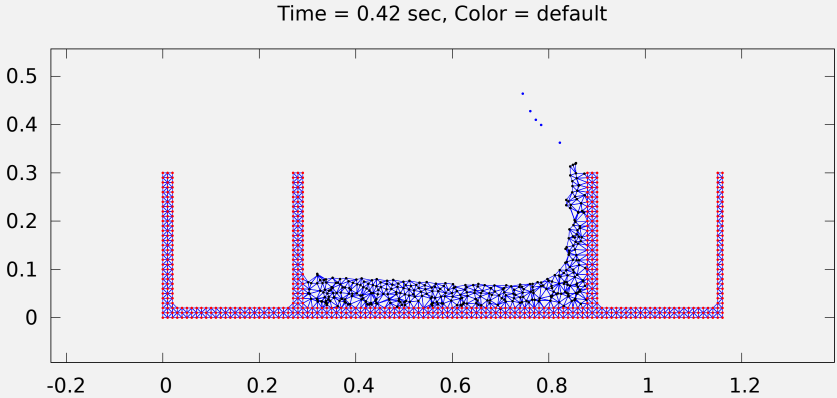

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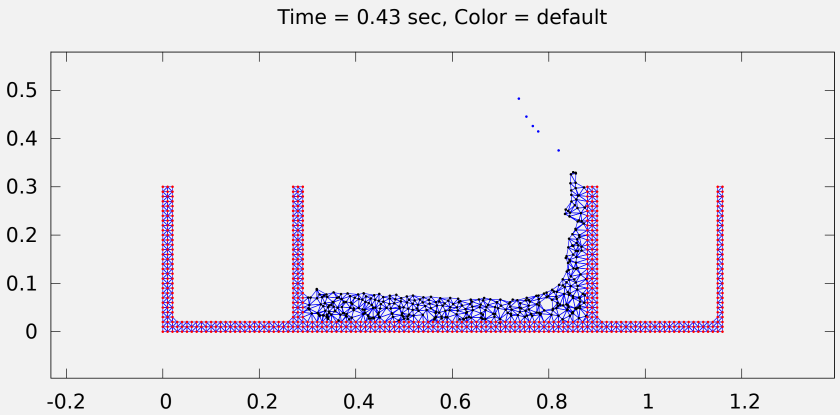

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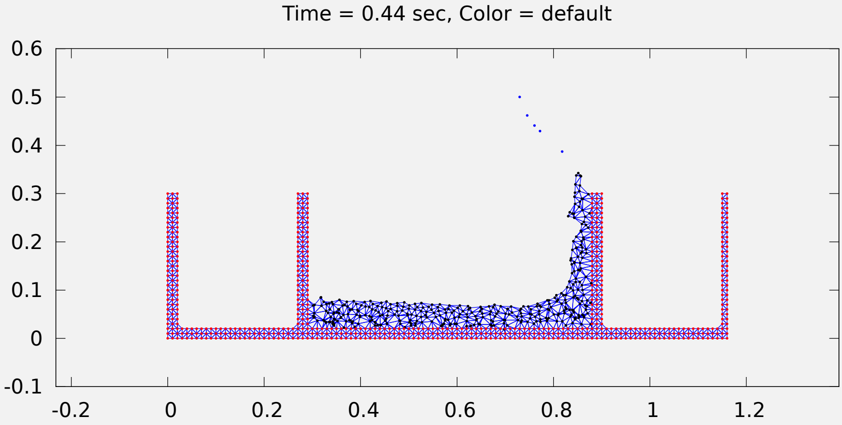

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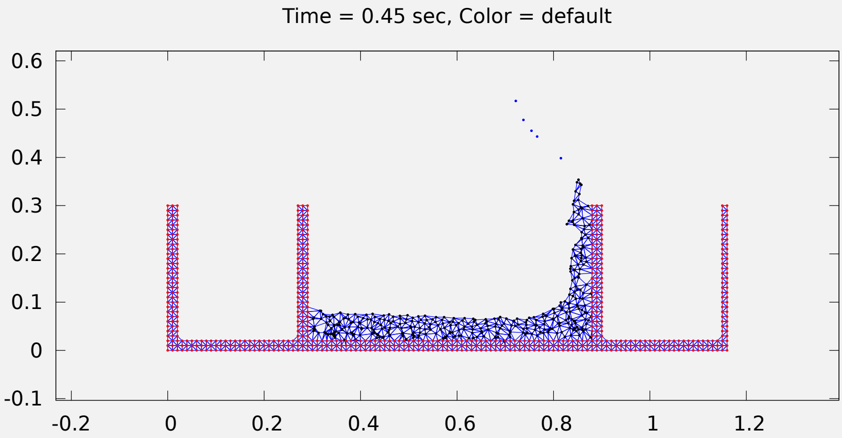

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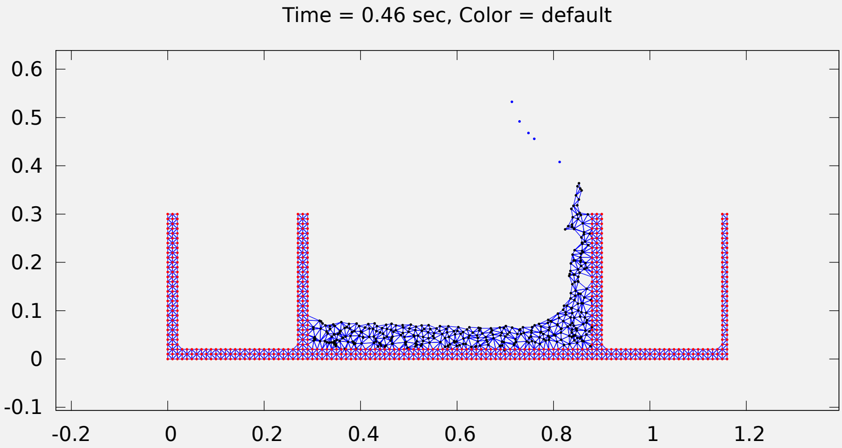

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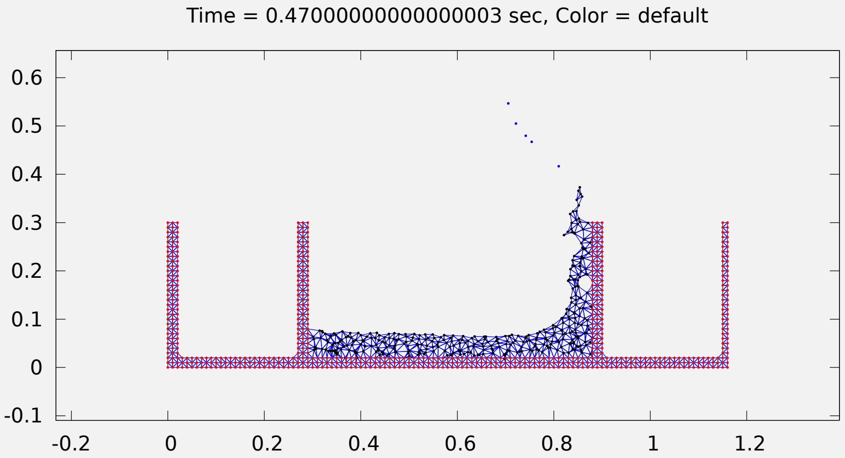

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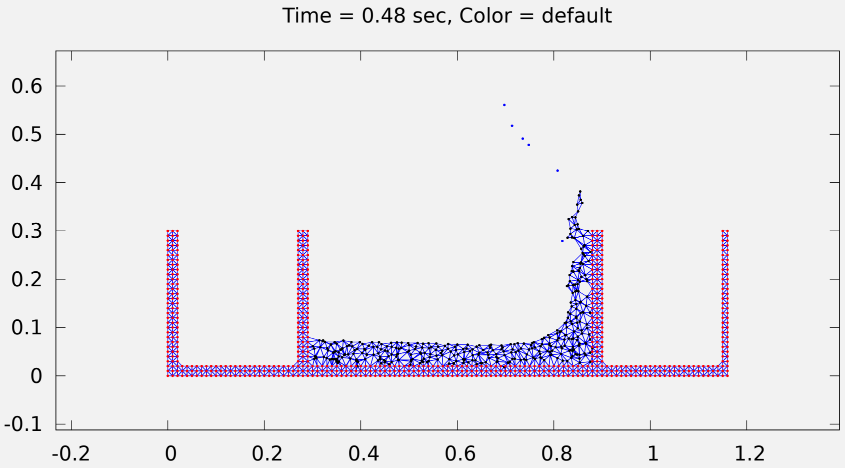

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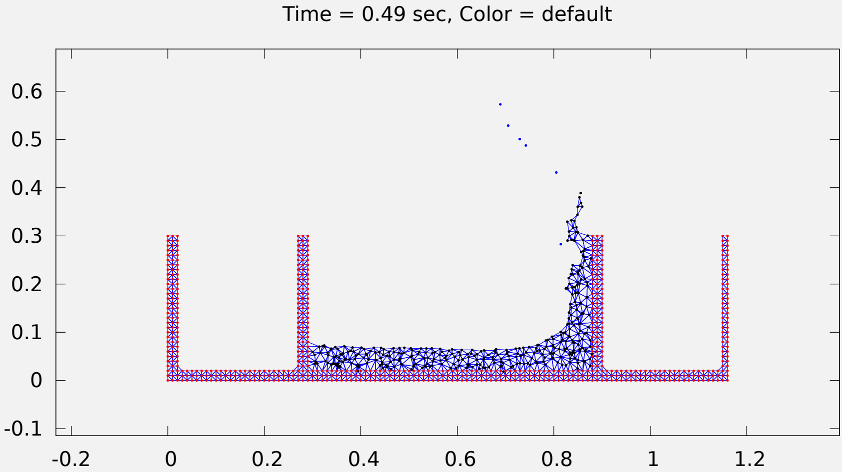

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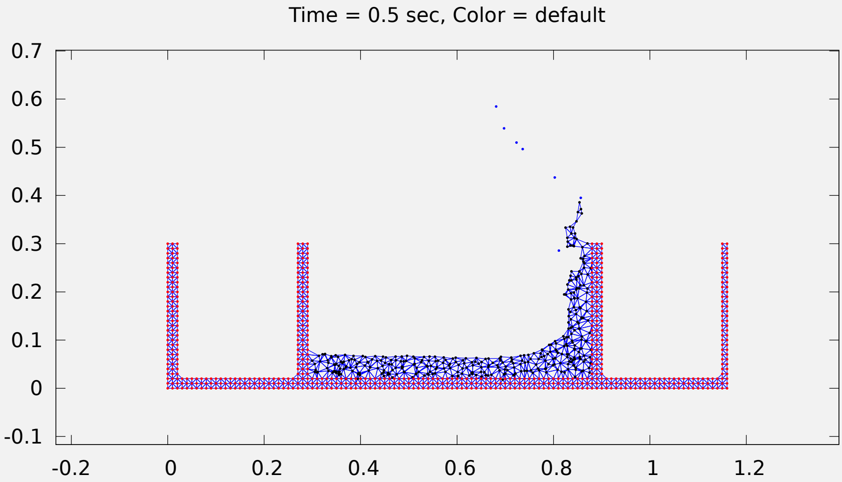

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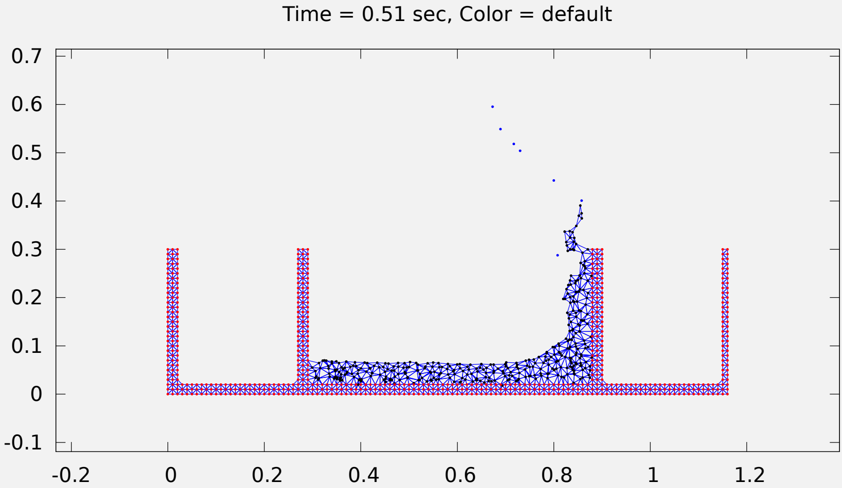

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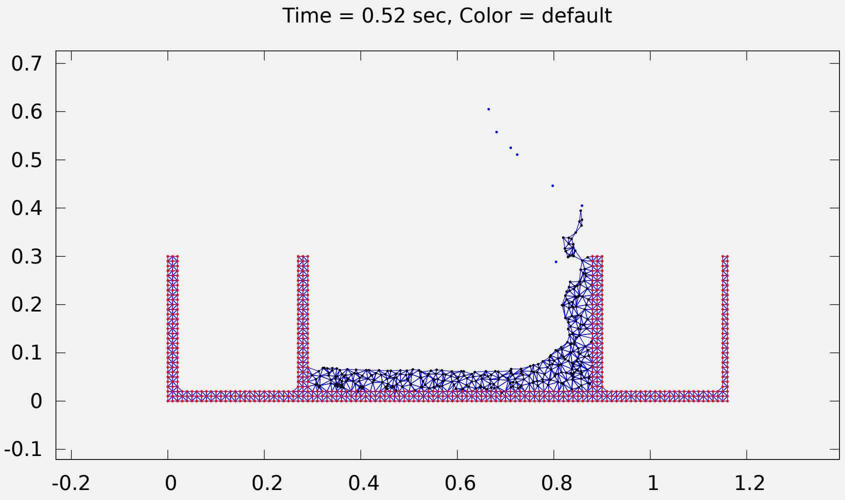

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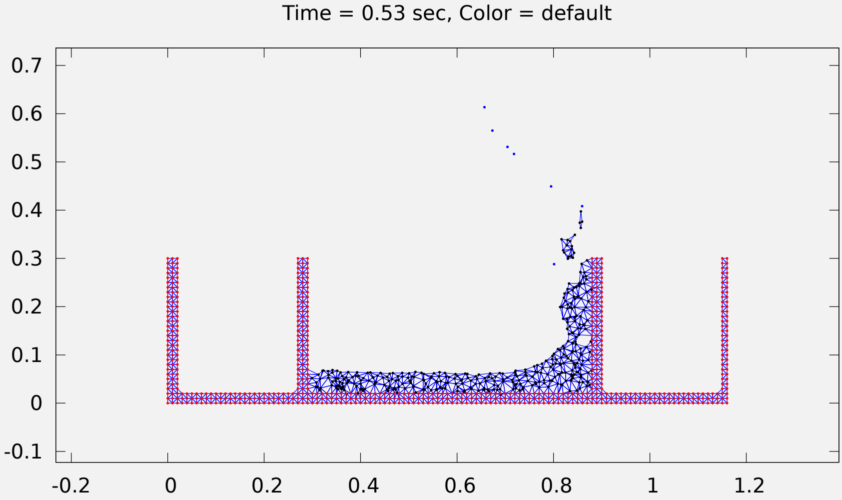

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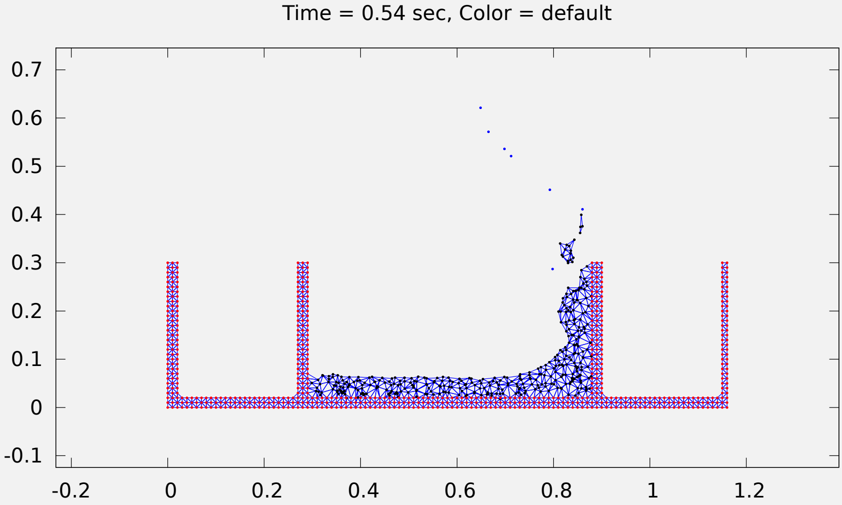

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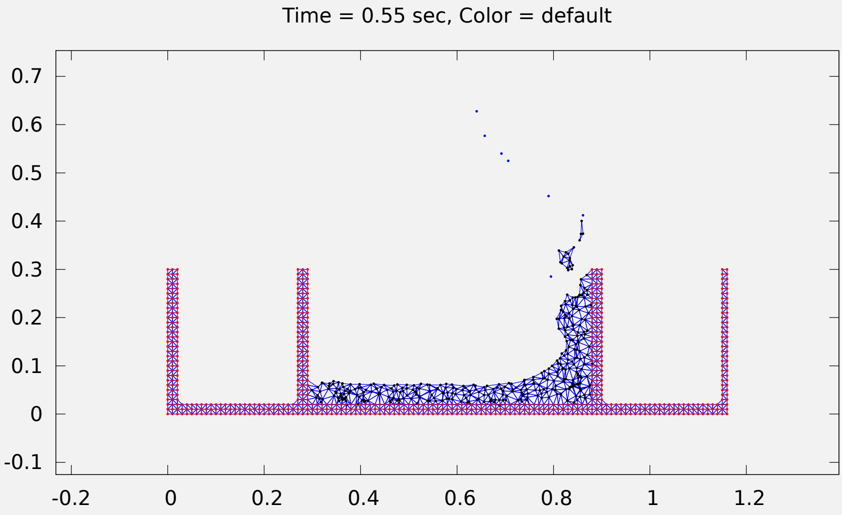

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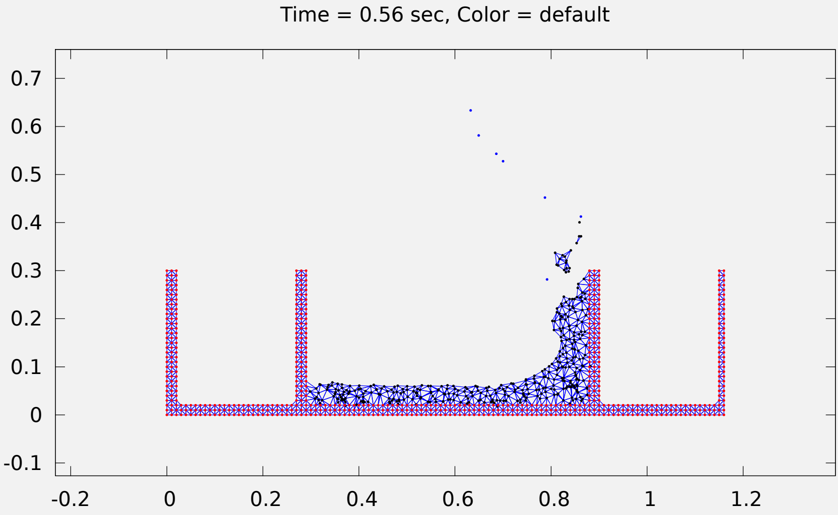

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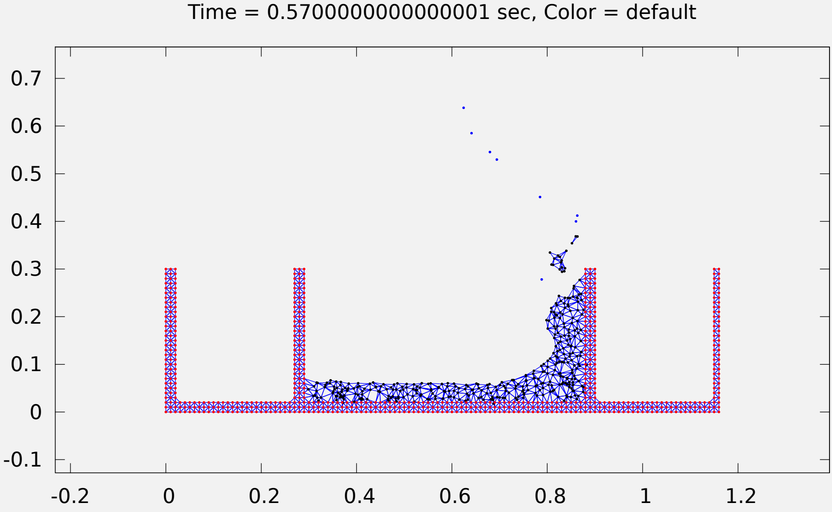

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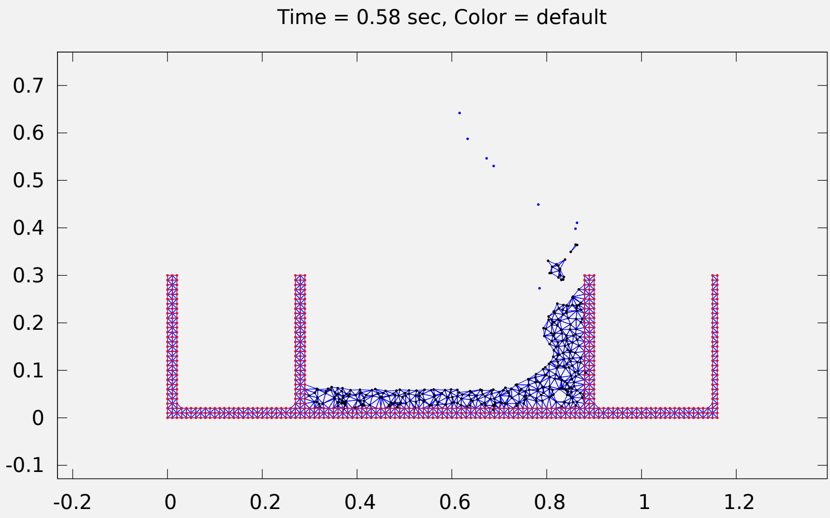

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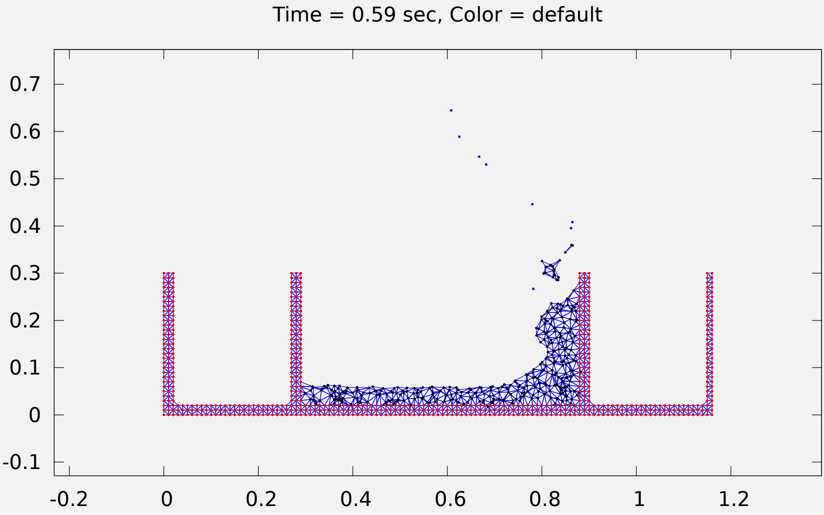

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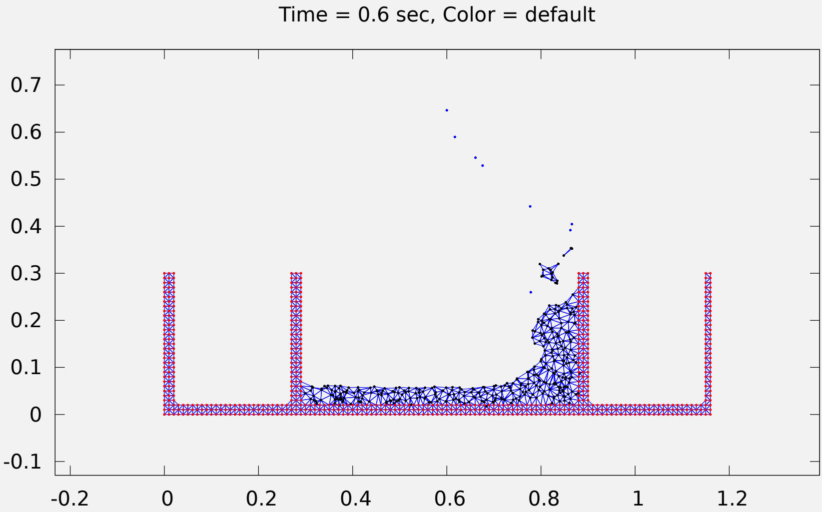

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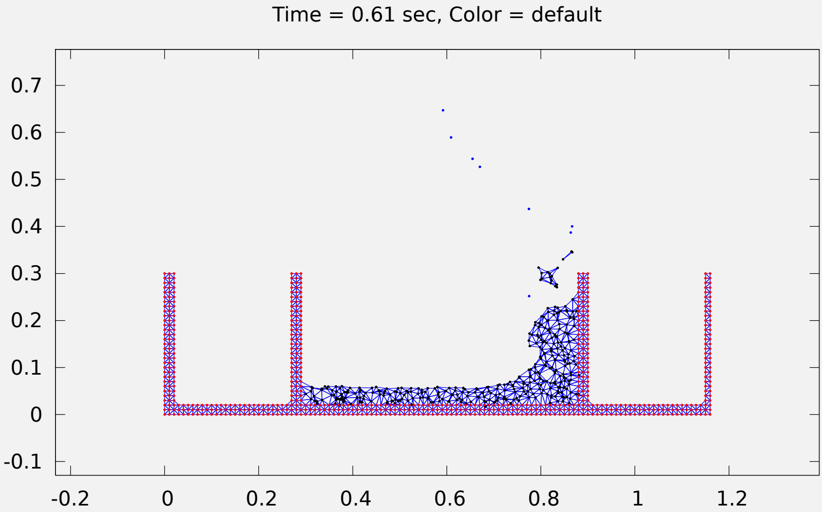

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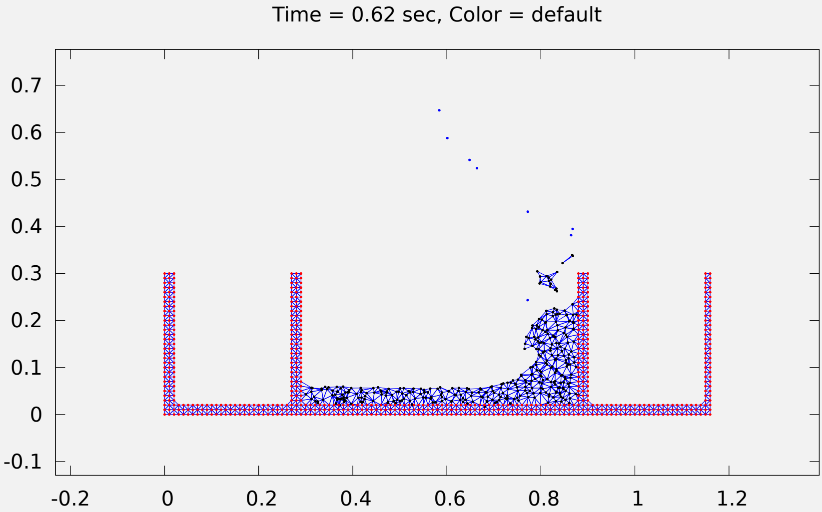

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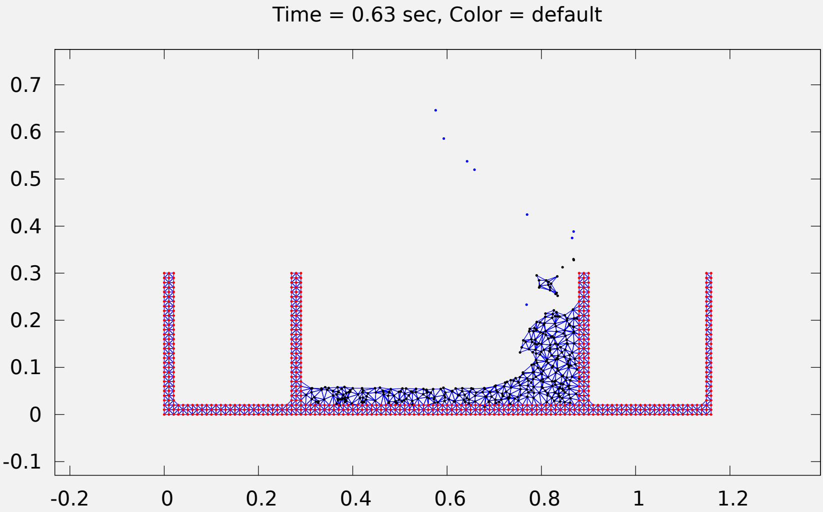

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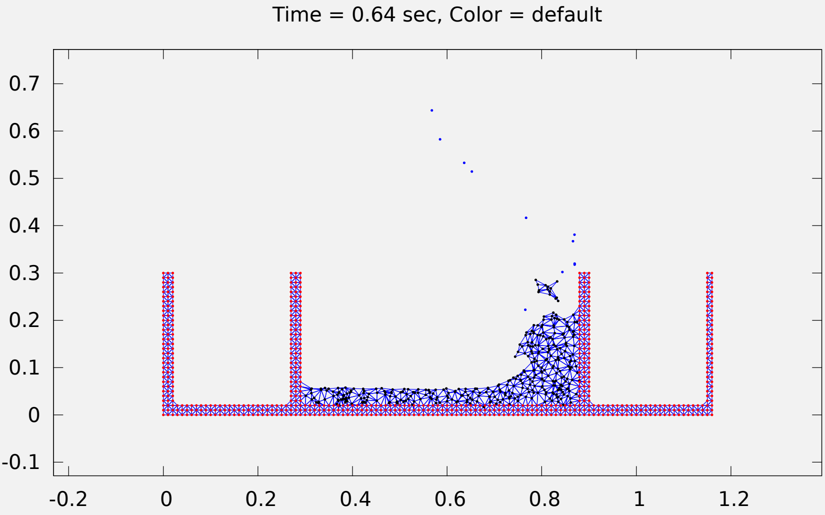

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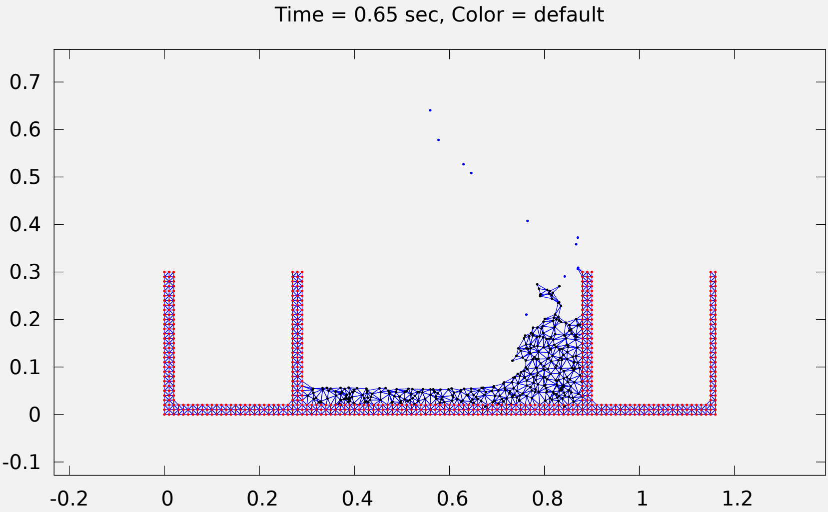

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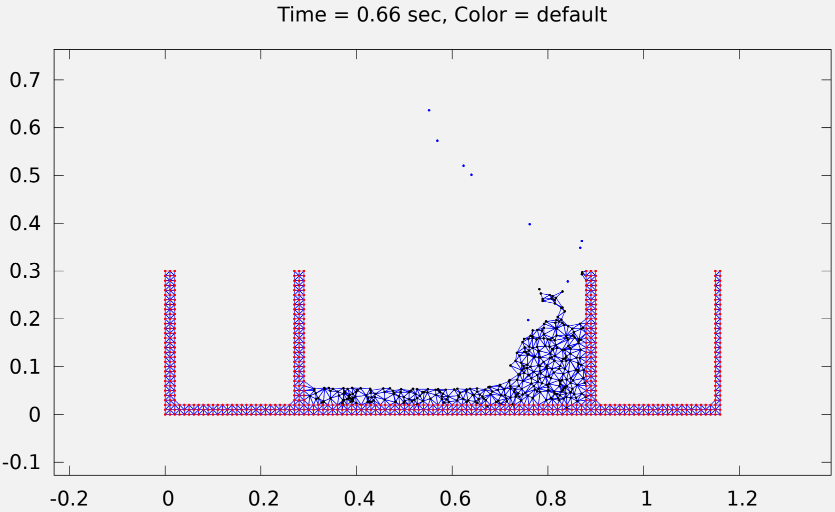

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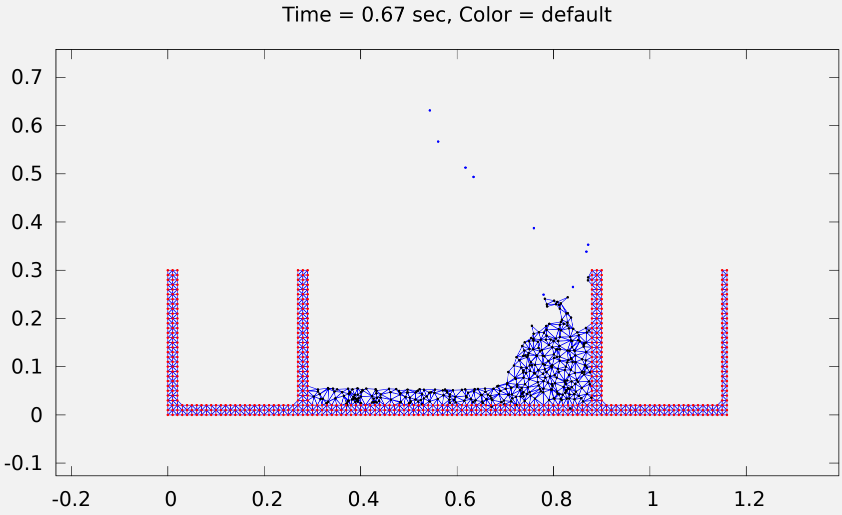

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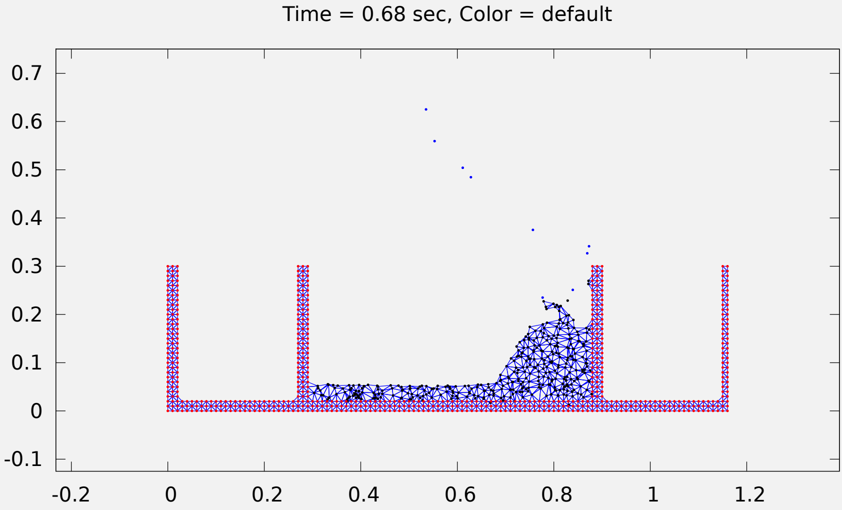

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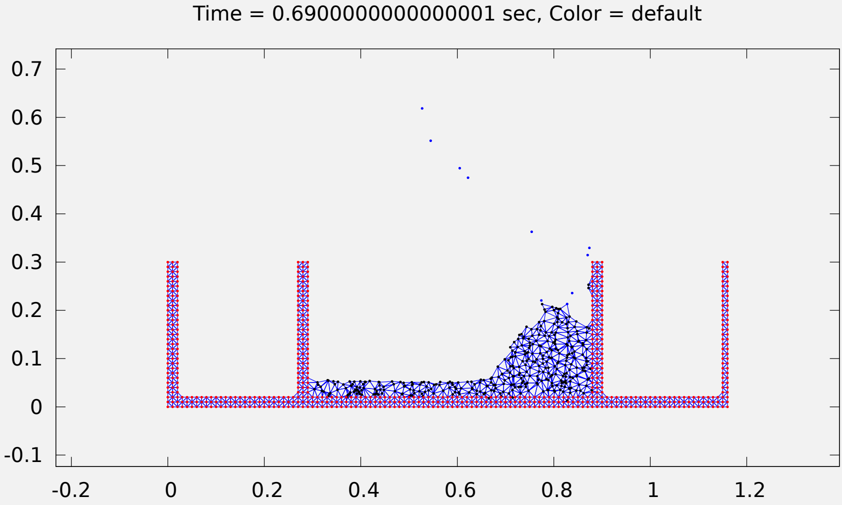

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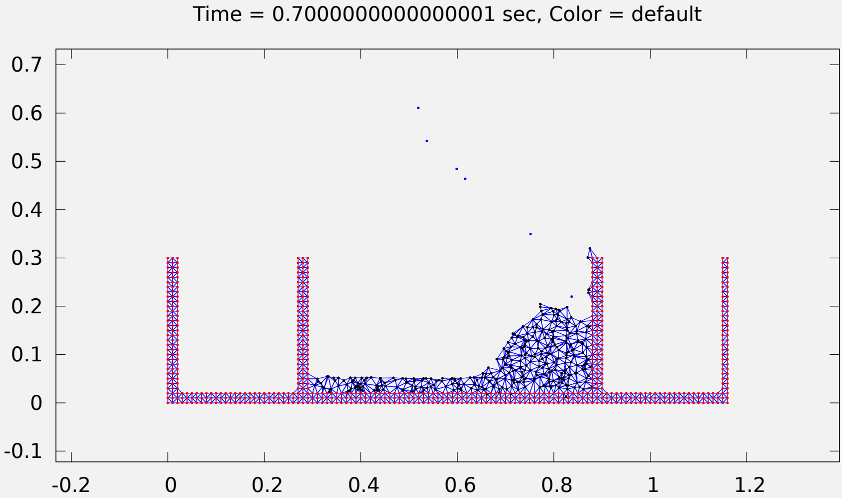

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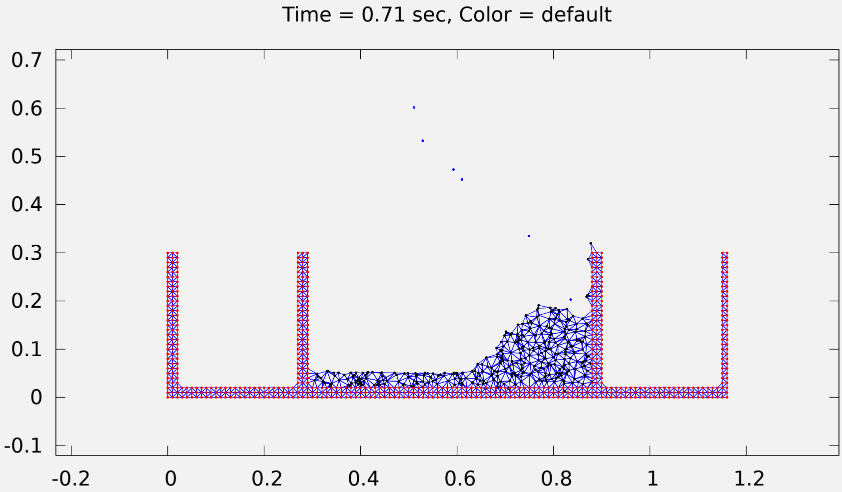

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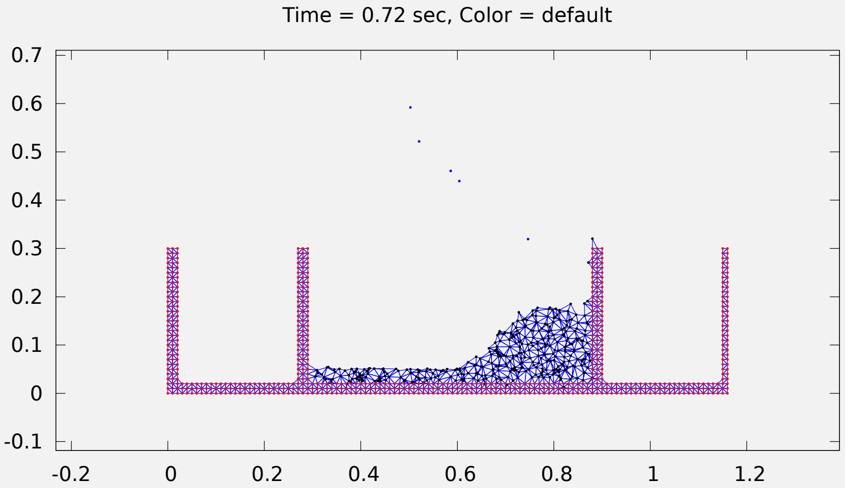

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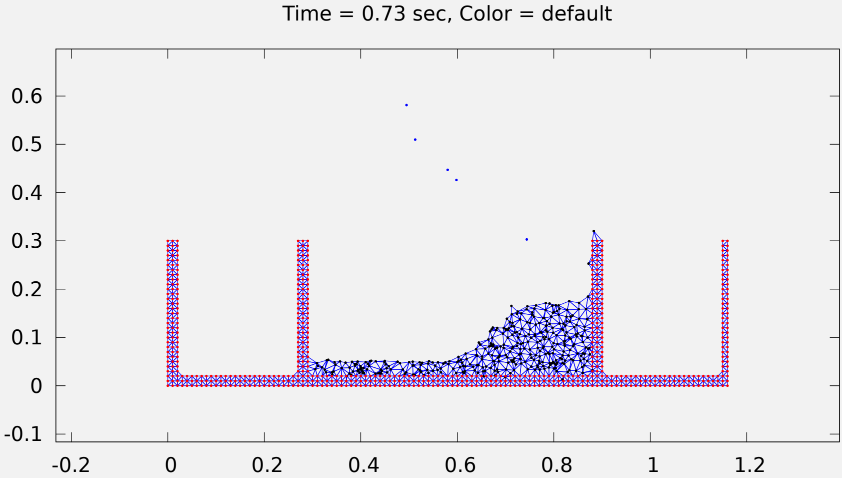

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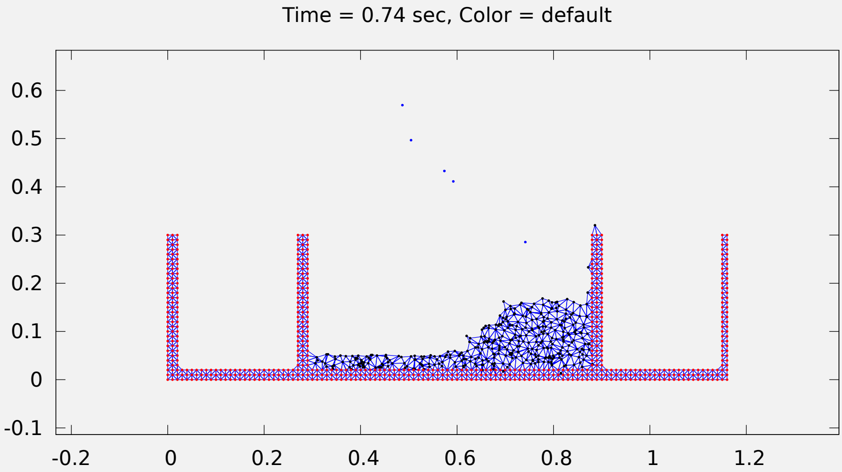

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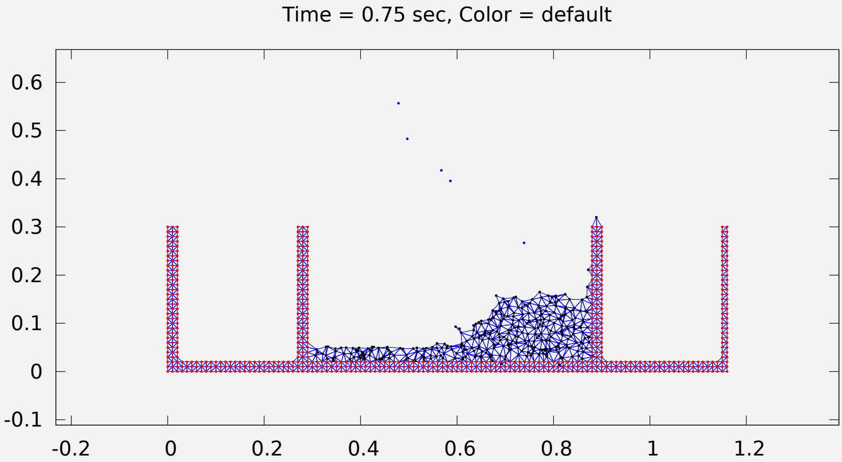

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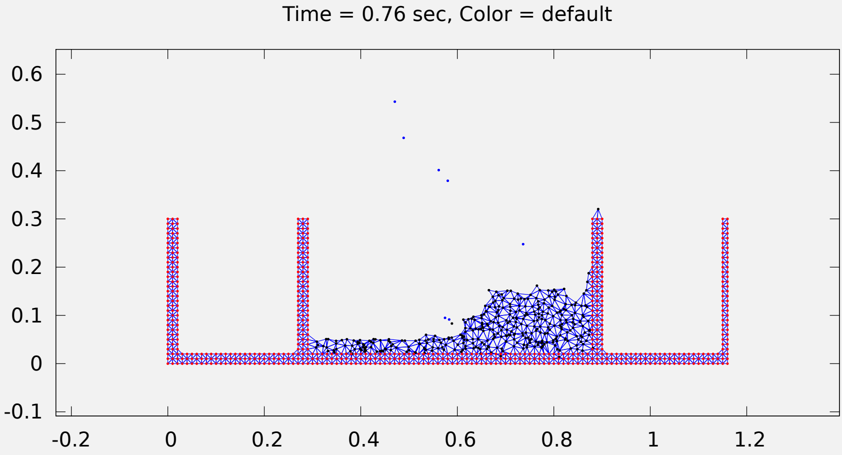

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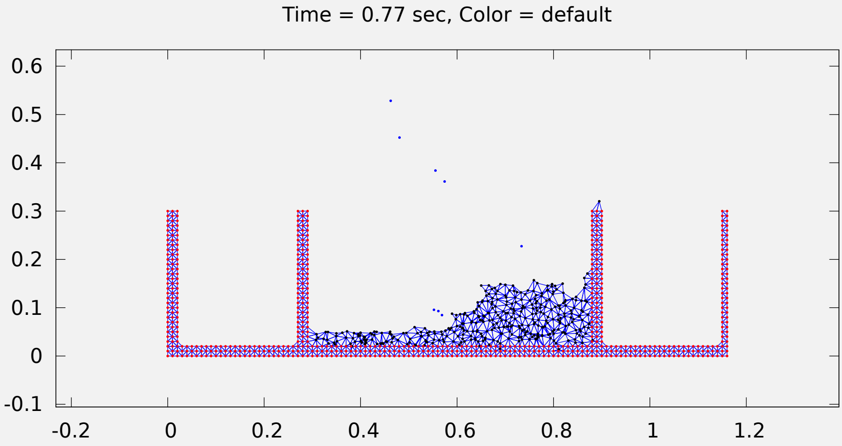

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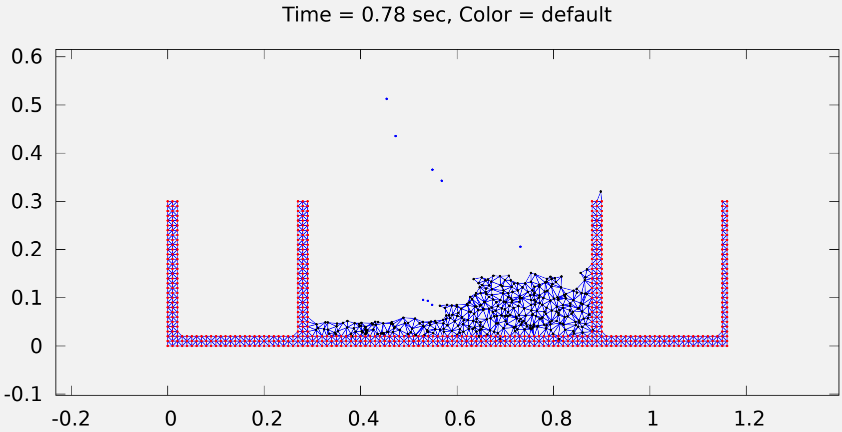

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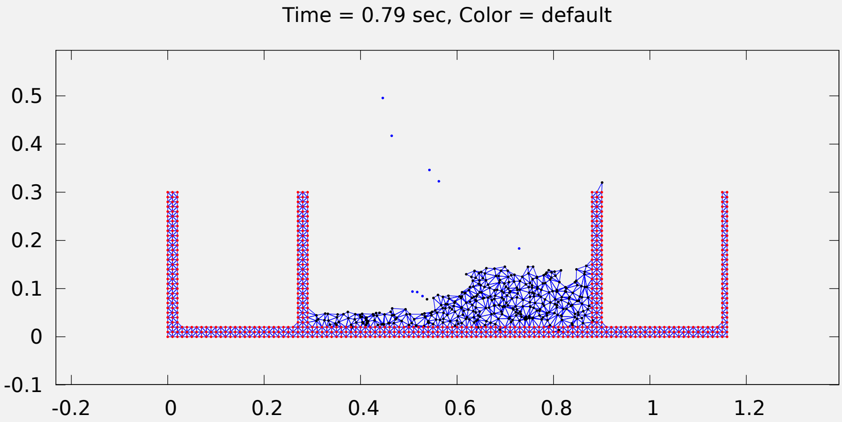

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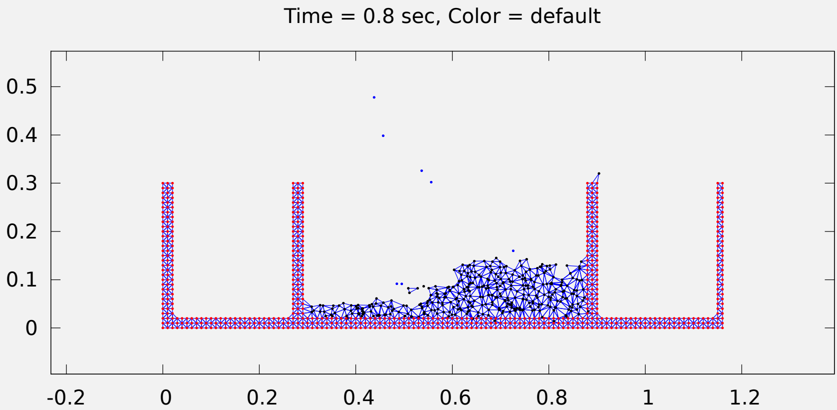

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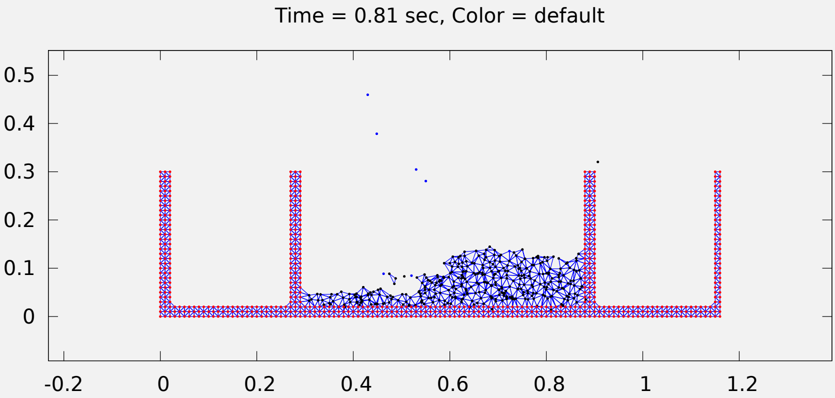

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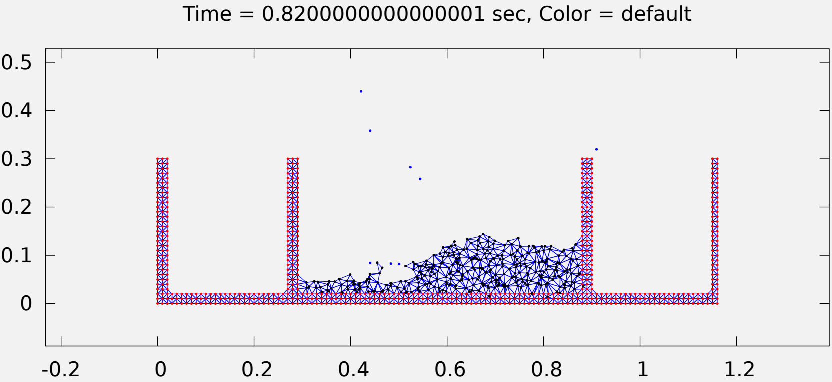

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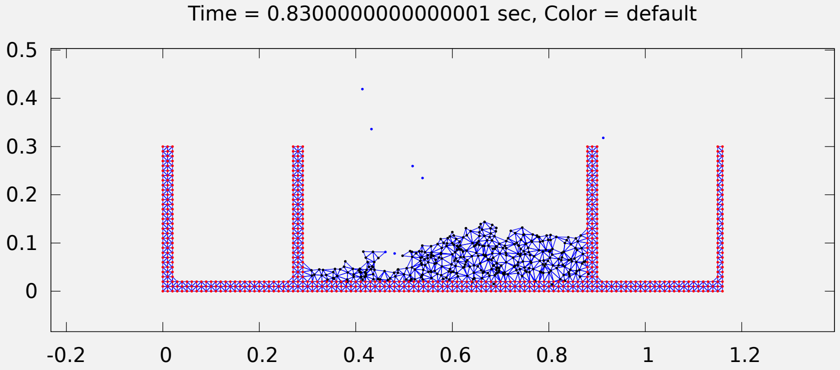

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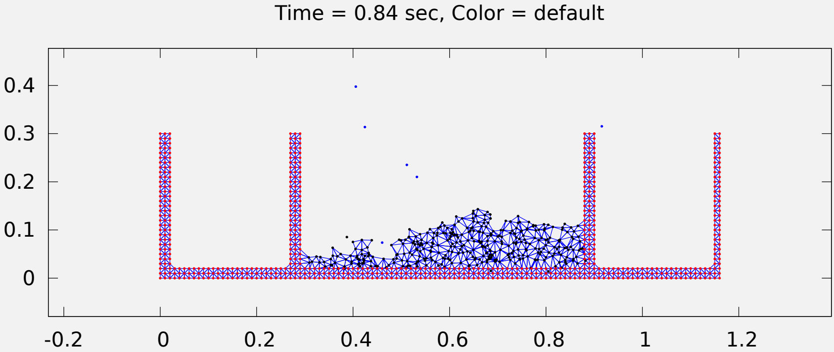

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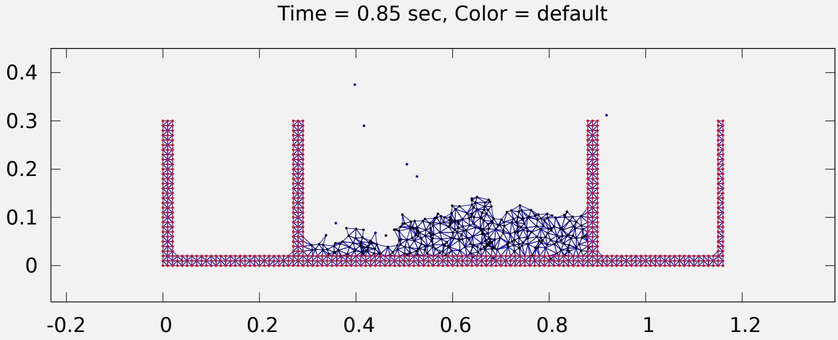

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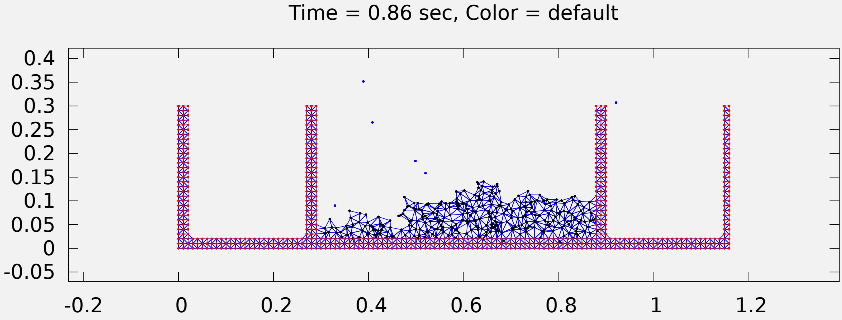

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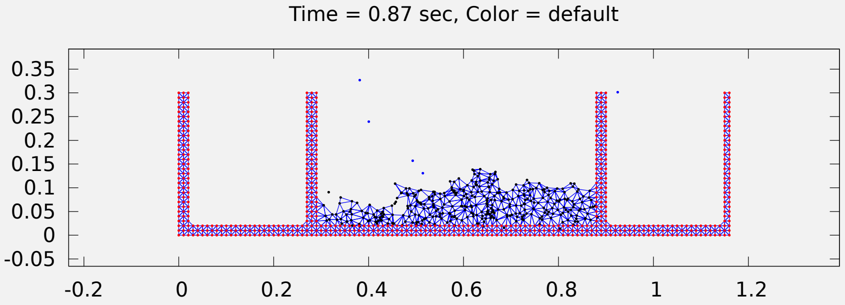

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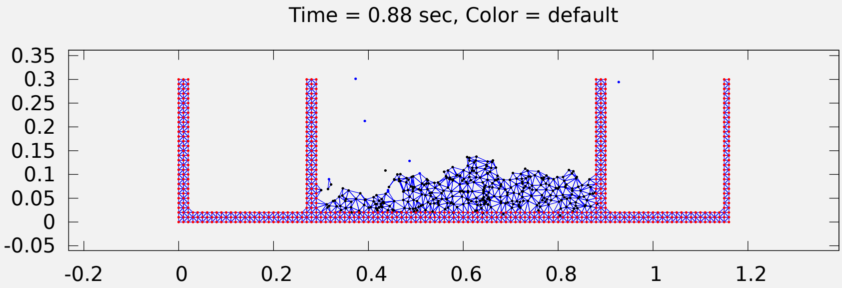

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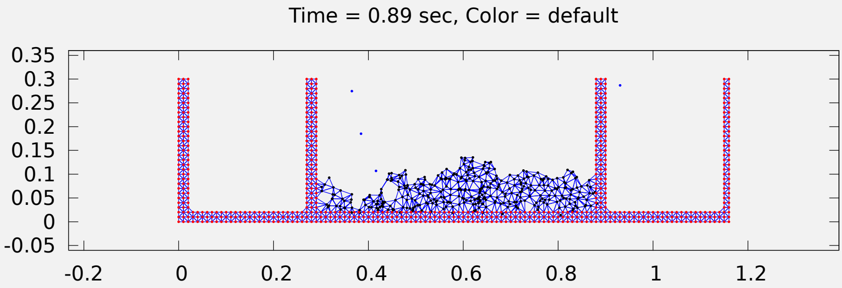

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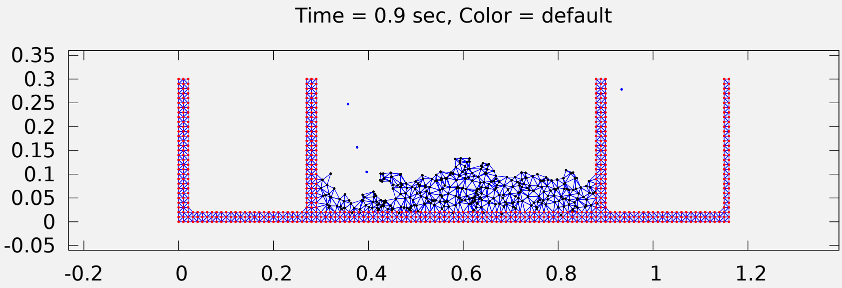

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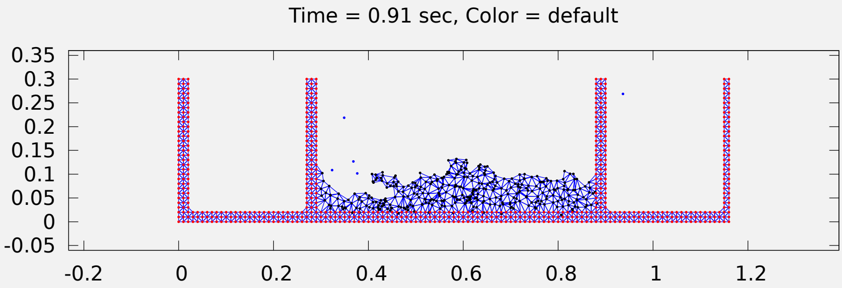

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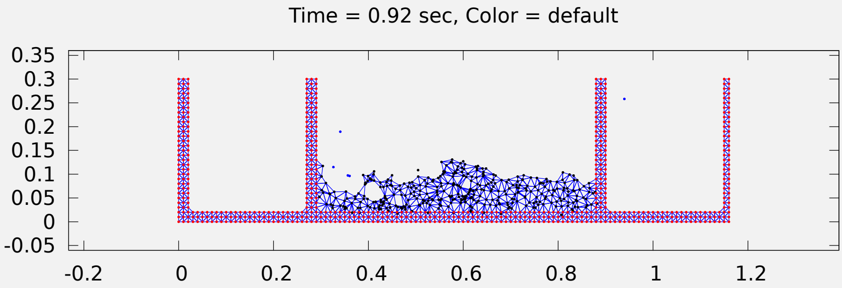

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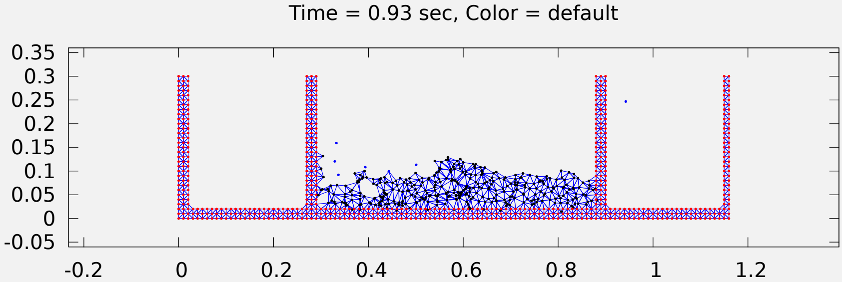

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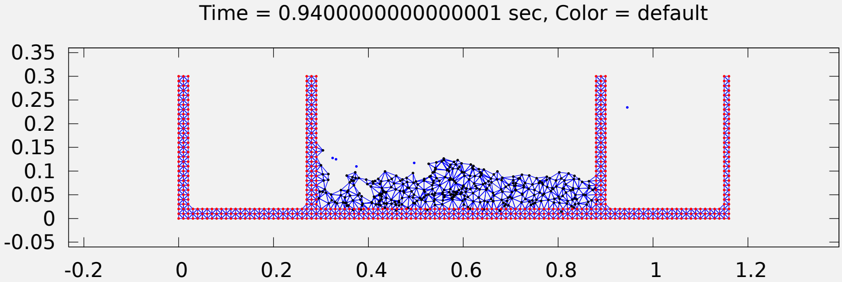

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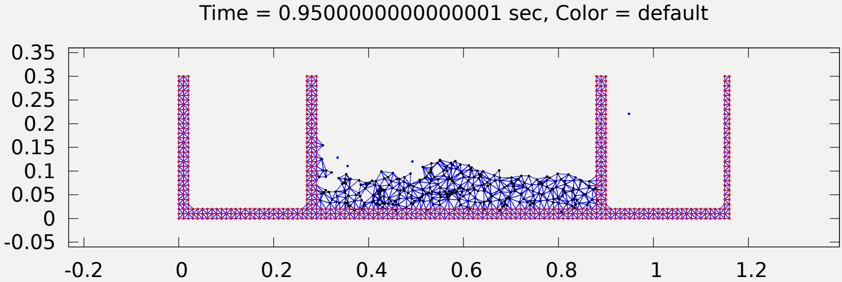

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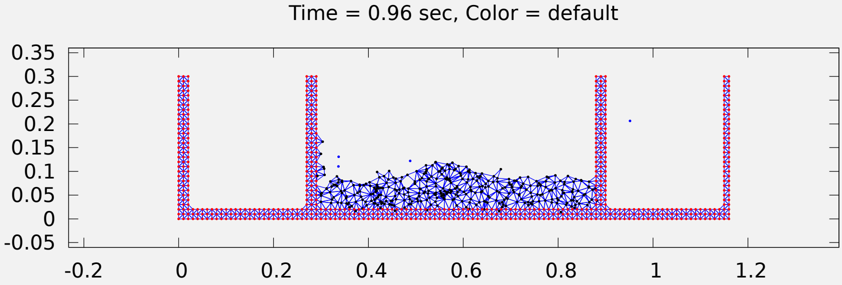

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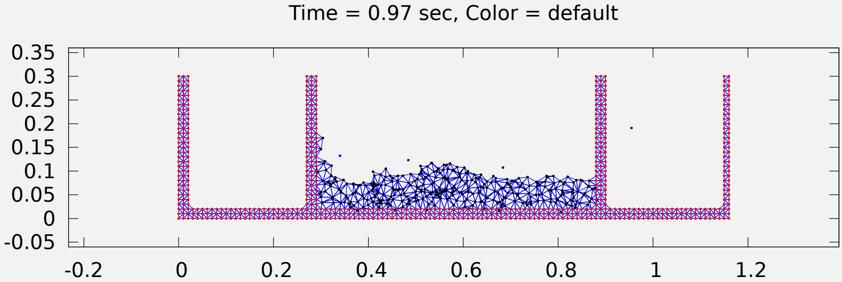

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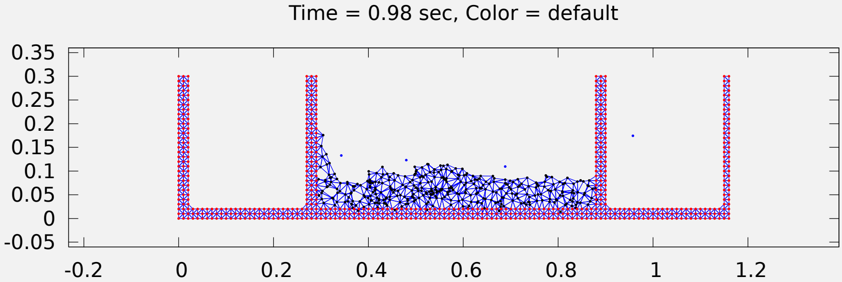

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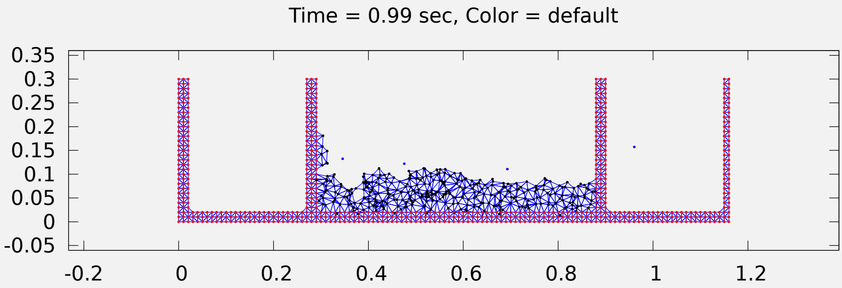
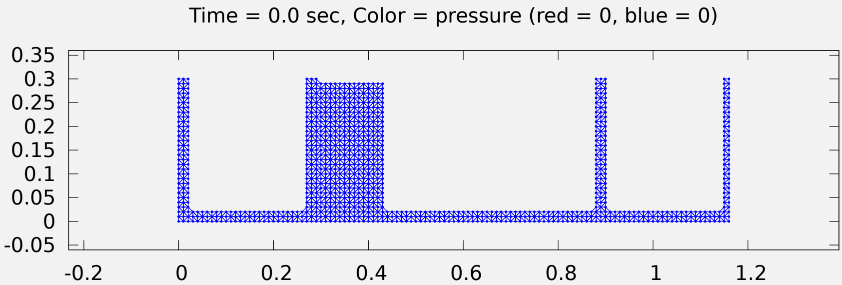


Water column collapse : pressure distribution



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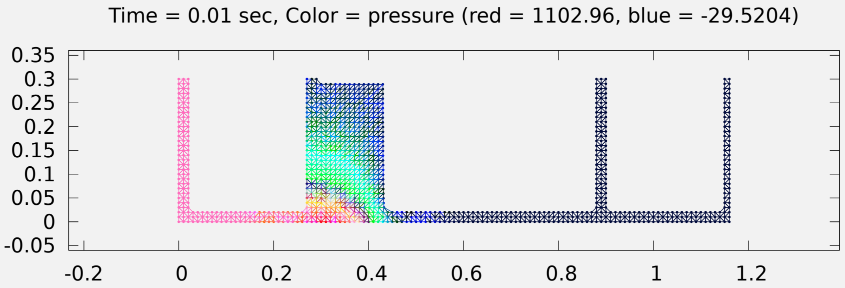
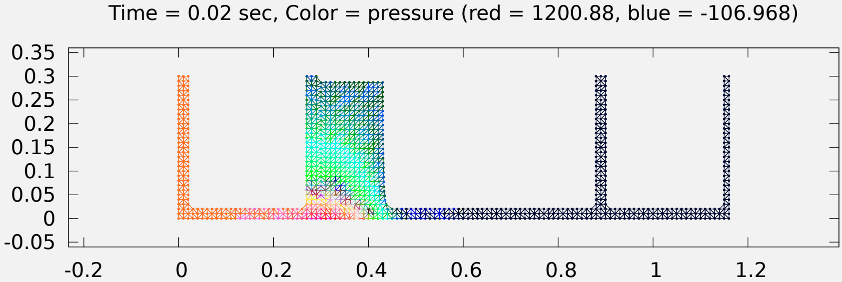


Water column collapse : pressure distribution



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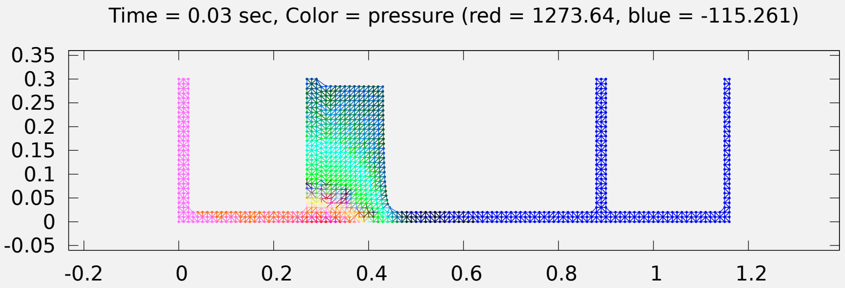

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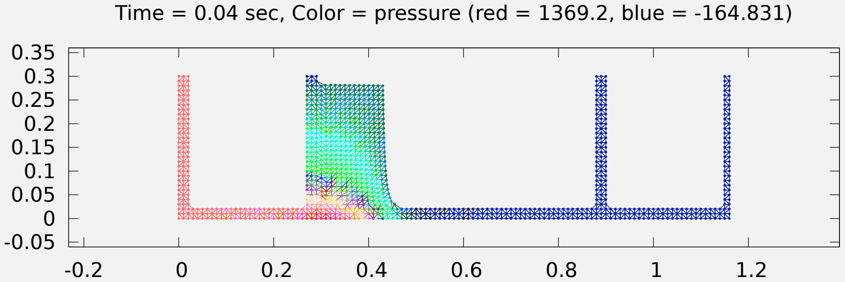

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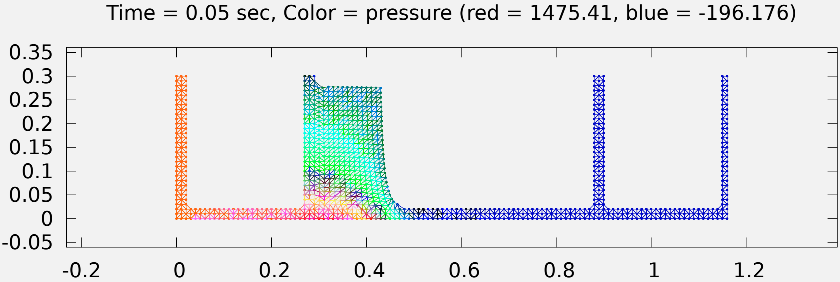

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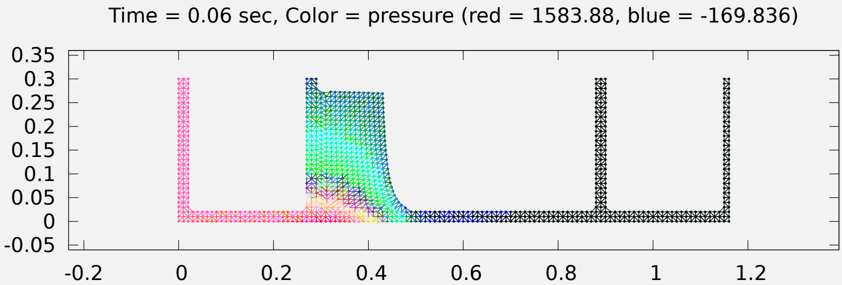

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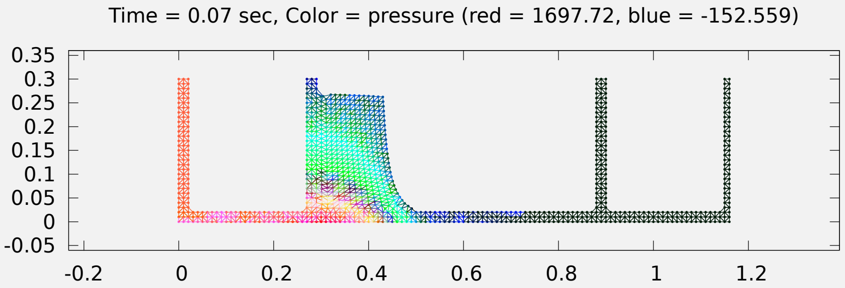

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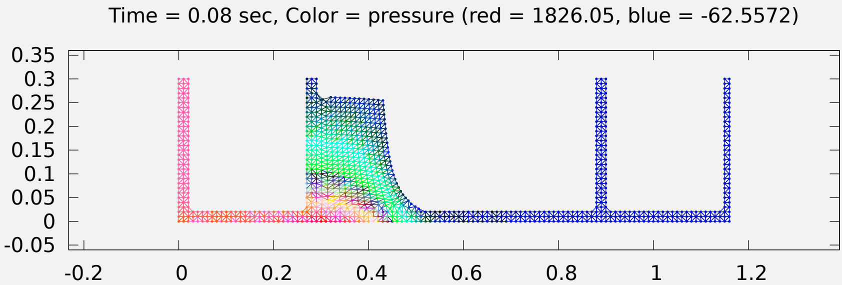

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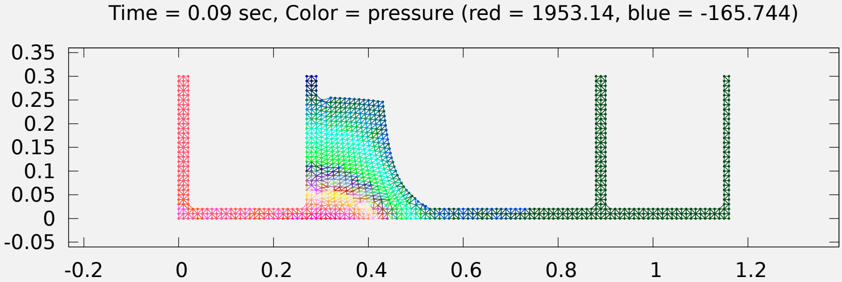

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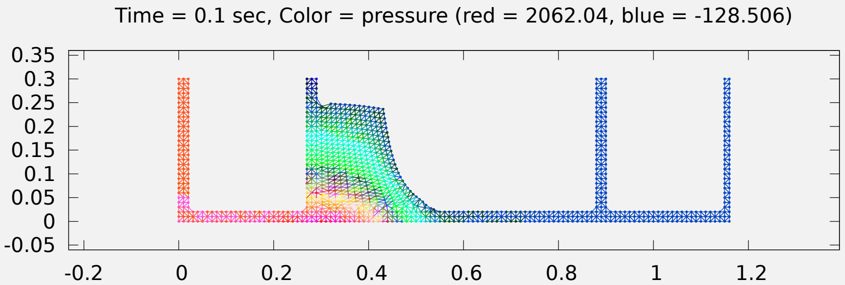

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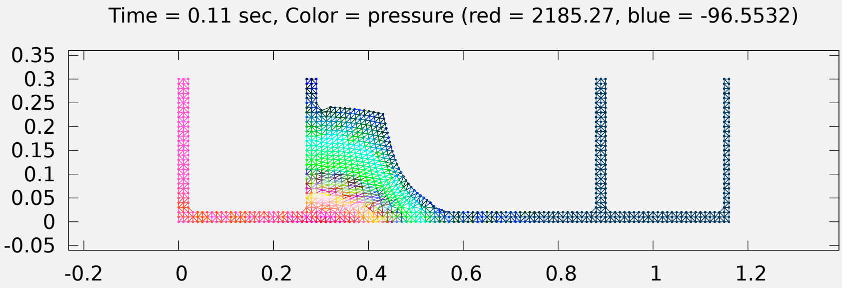

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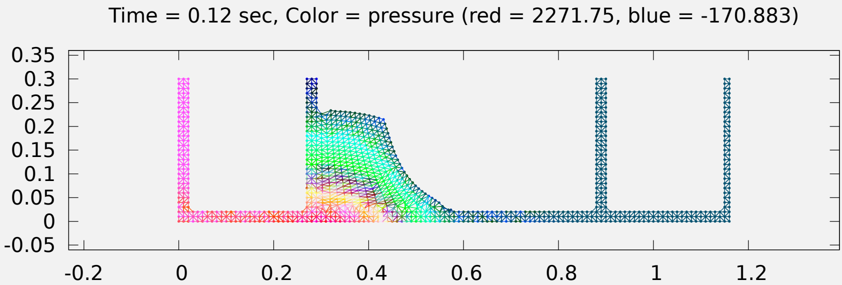

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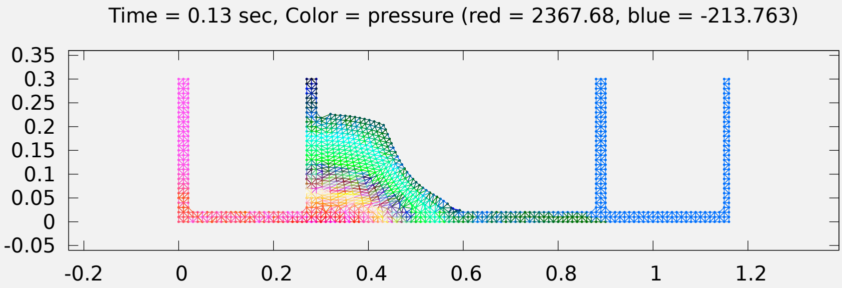

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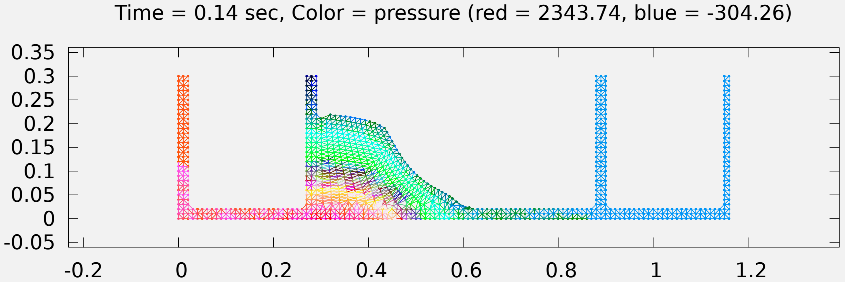

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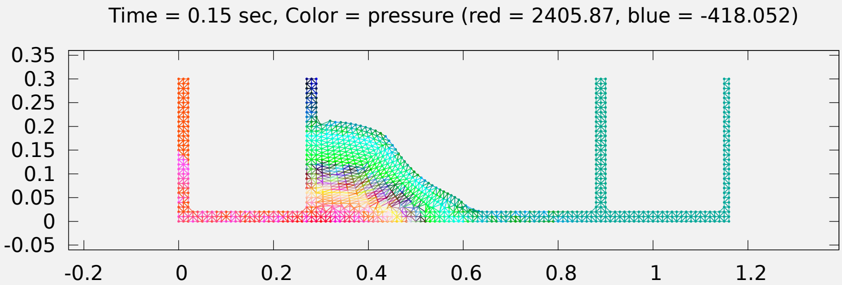

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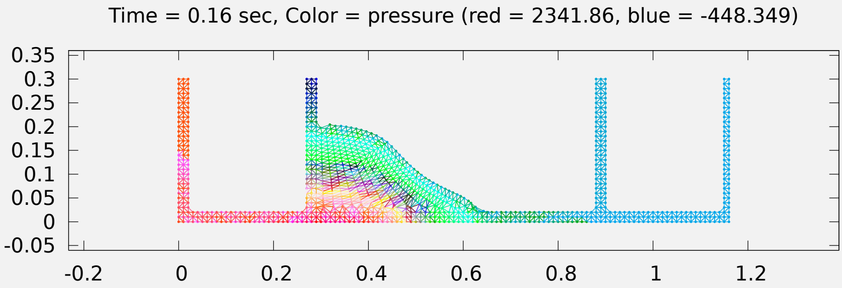

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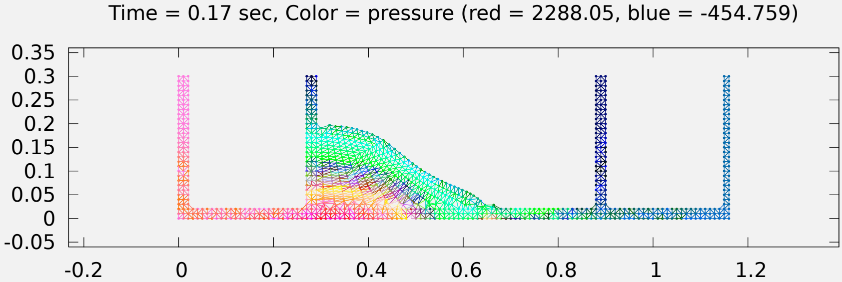

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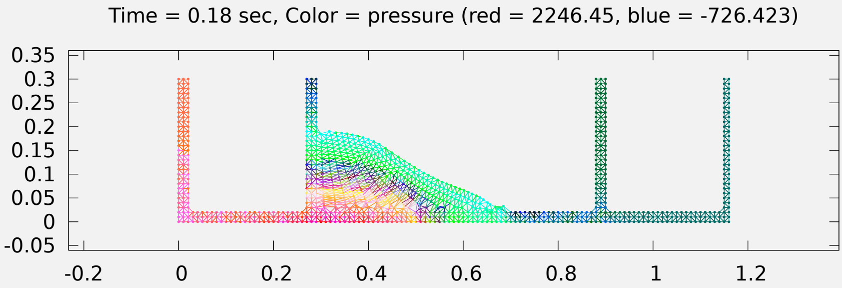

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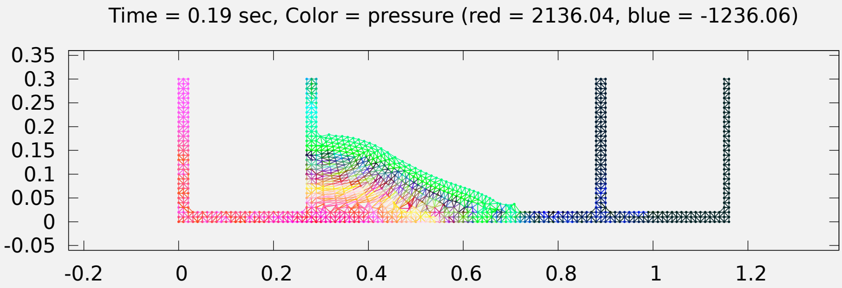

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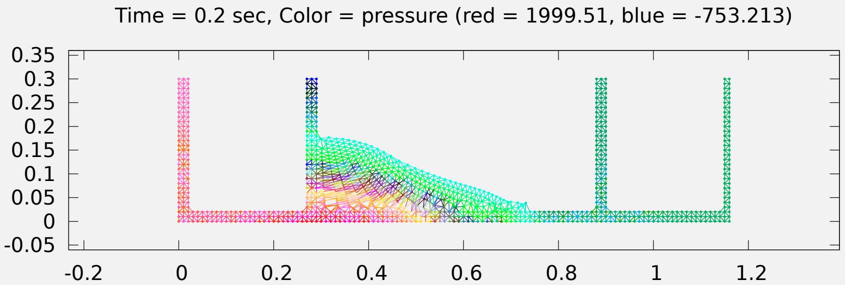

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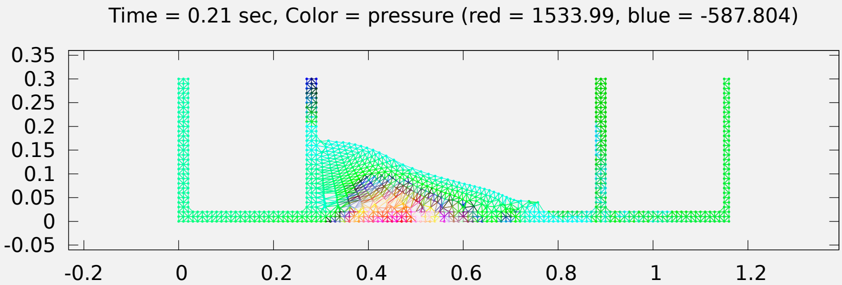

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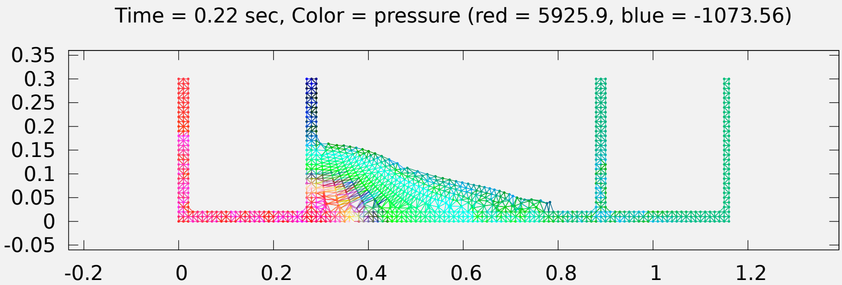

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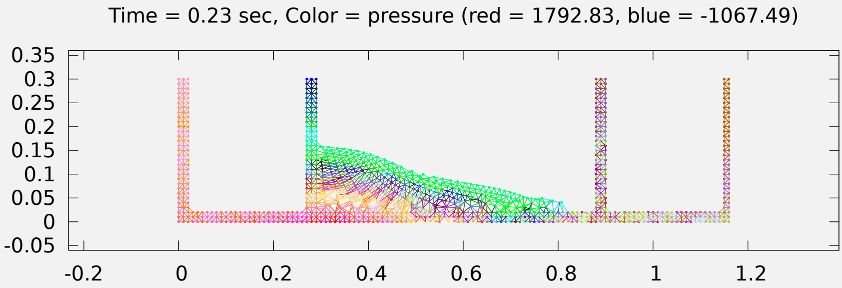

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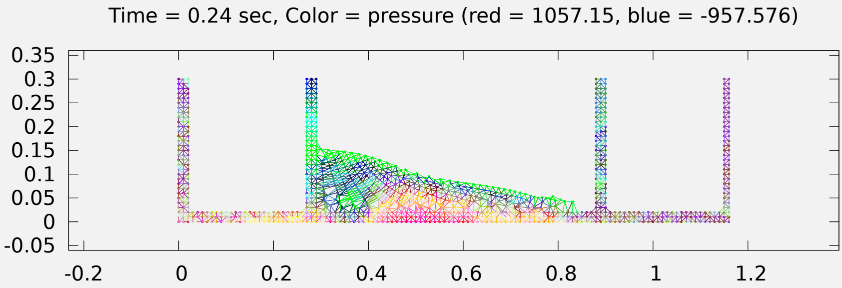

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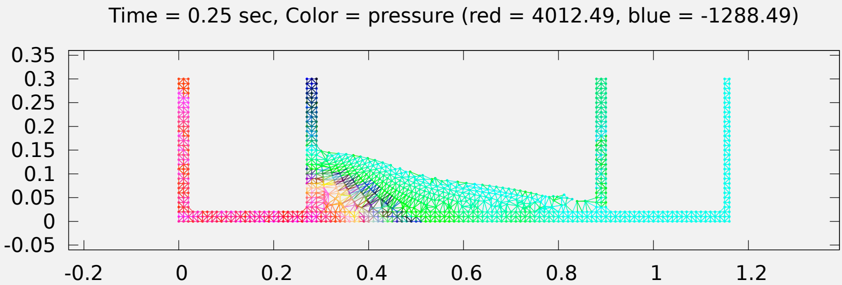

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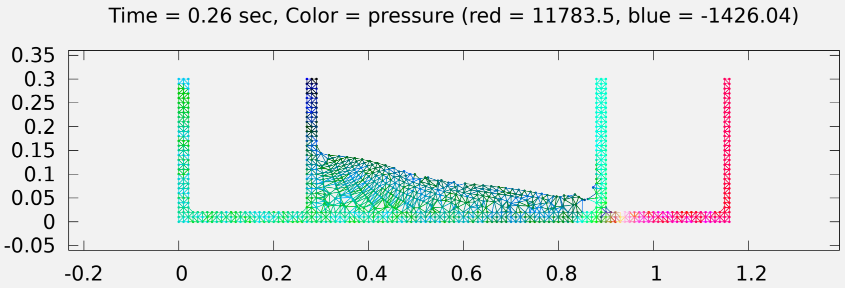

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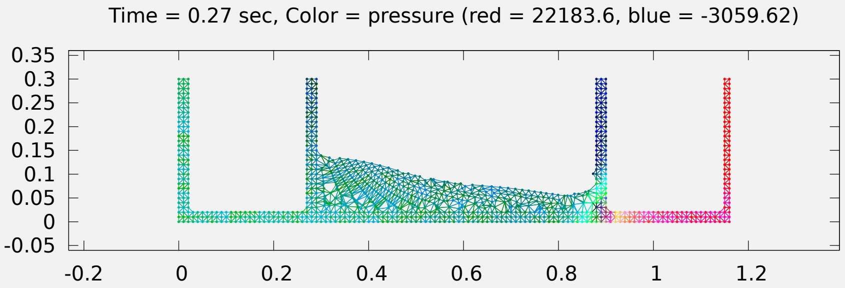

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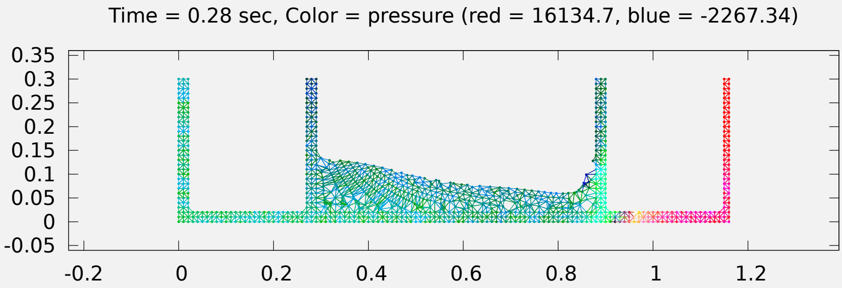

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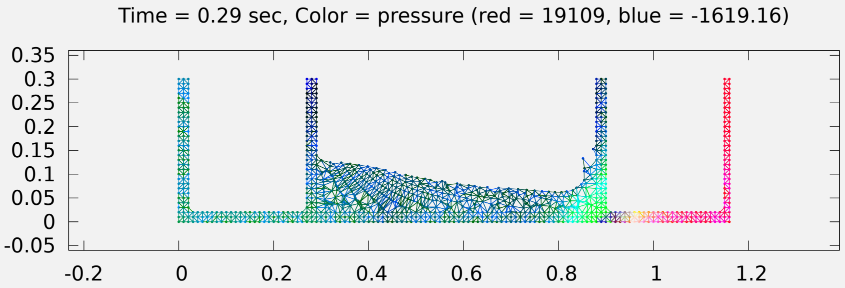

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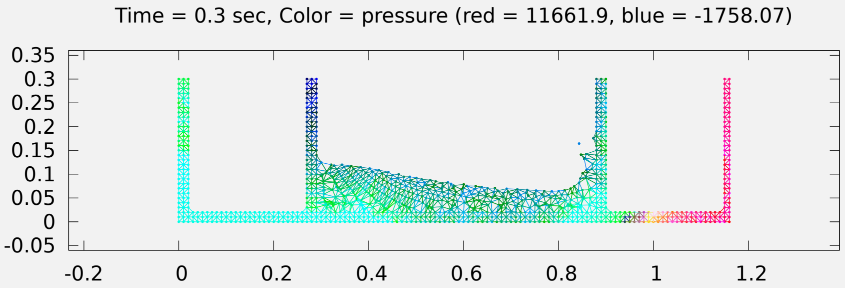

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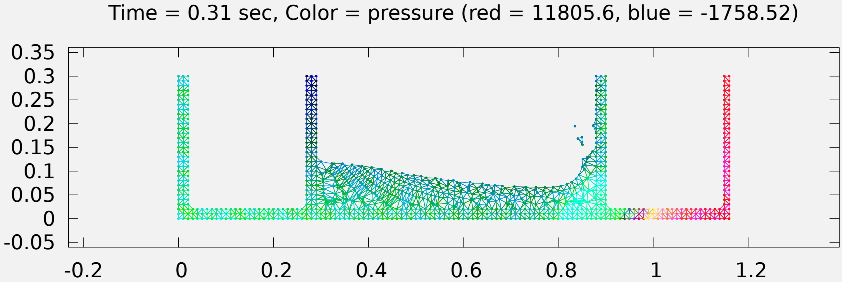

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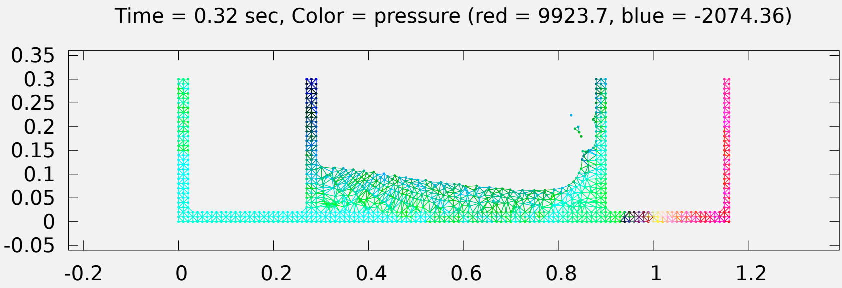

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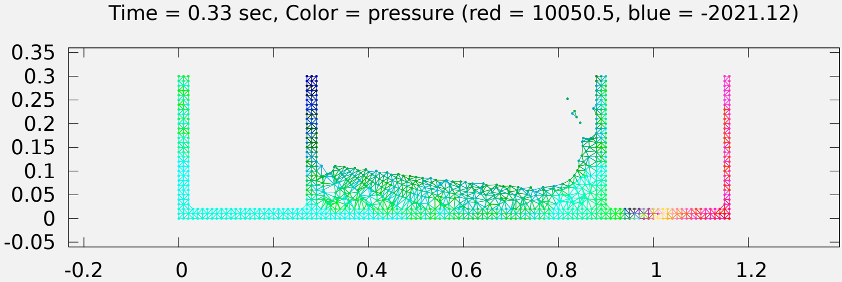

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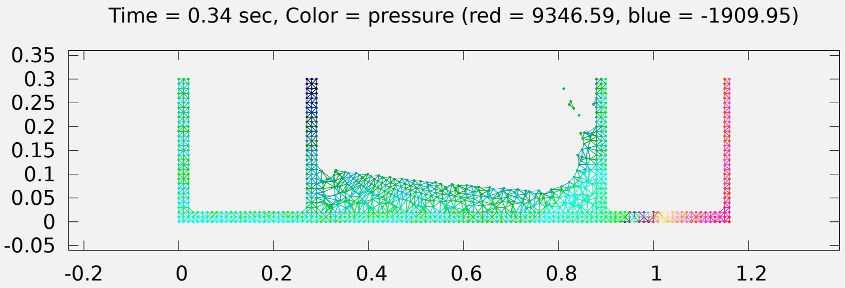

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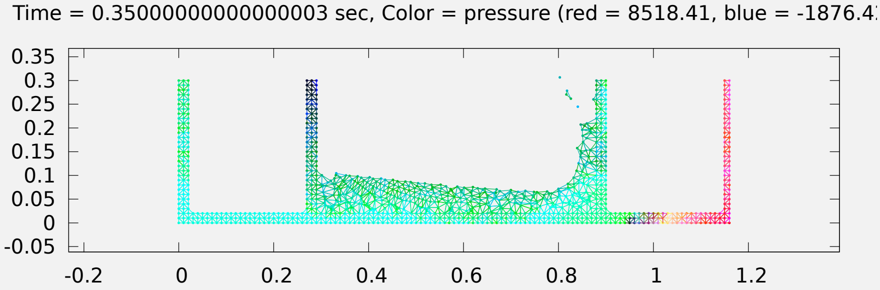

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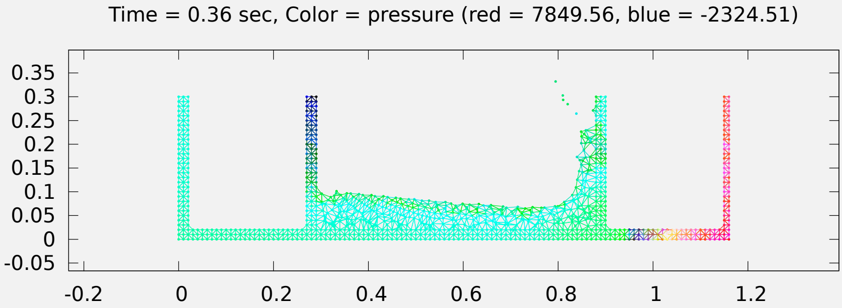

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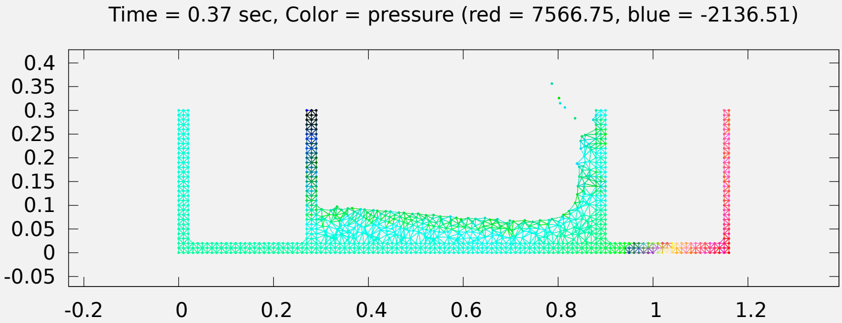

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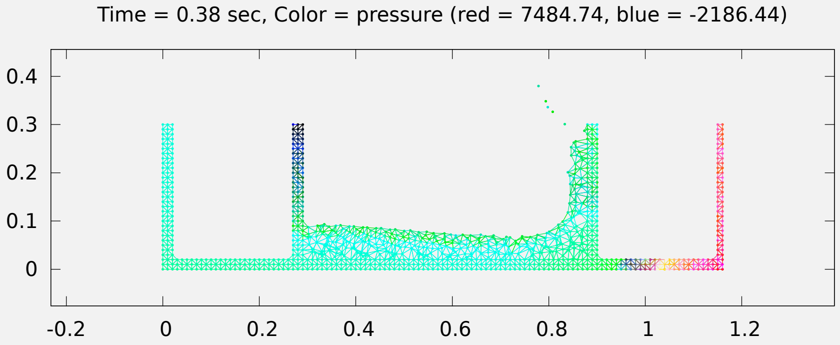

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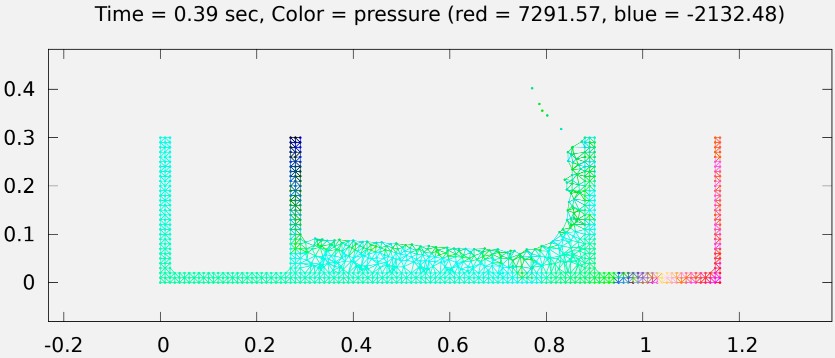

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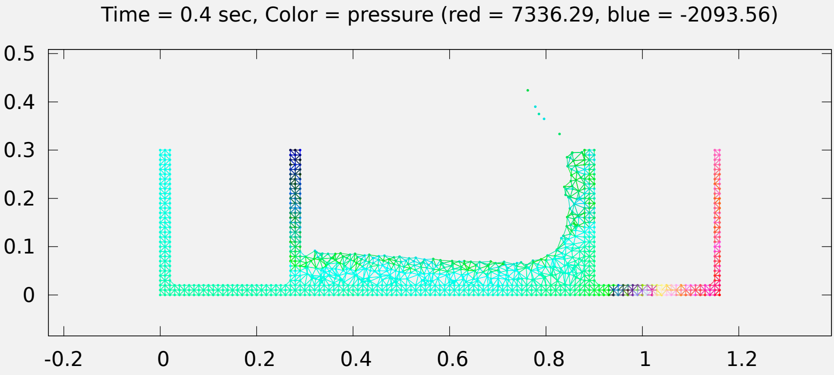

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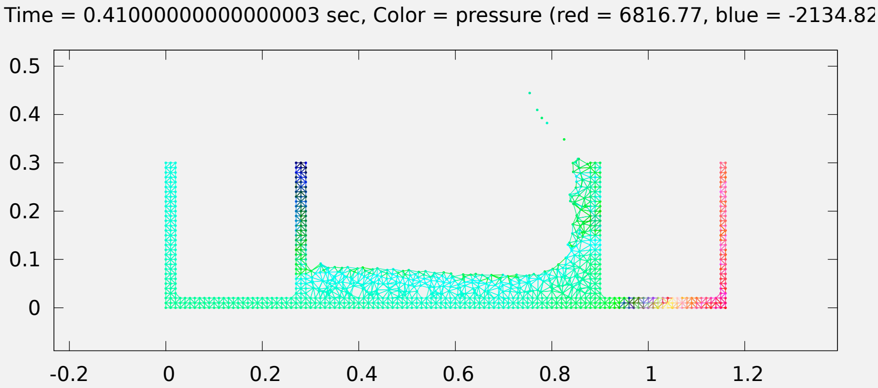

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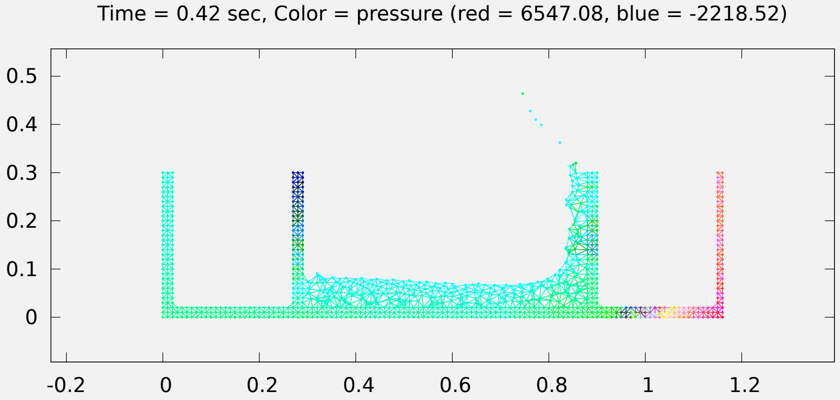

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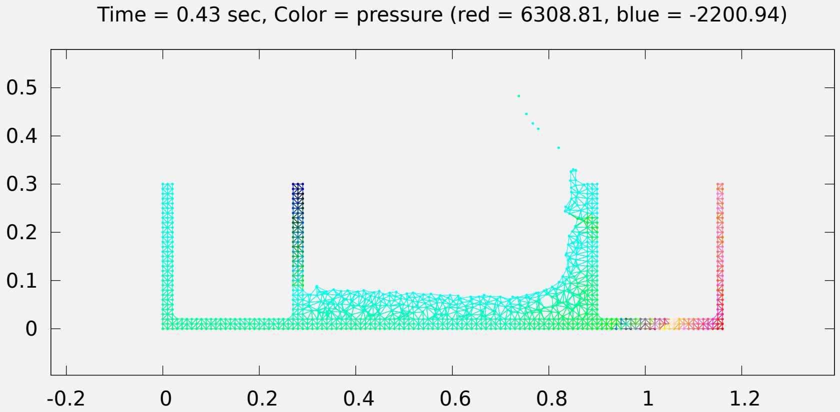

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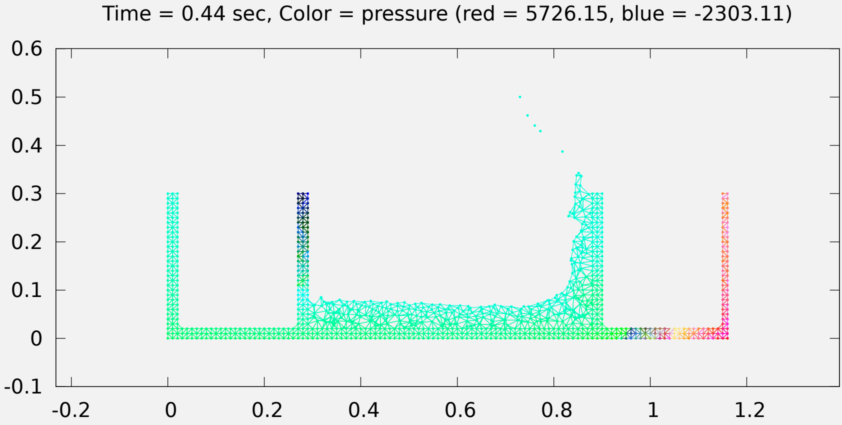

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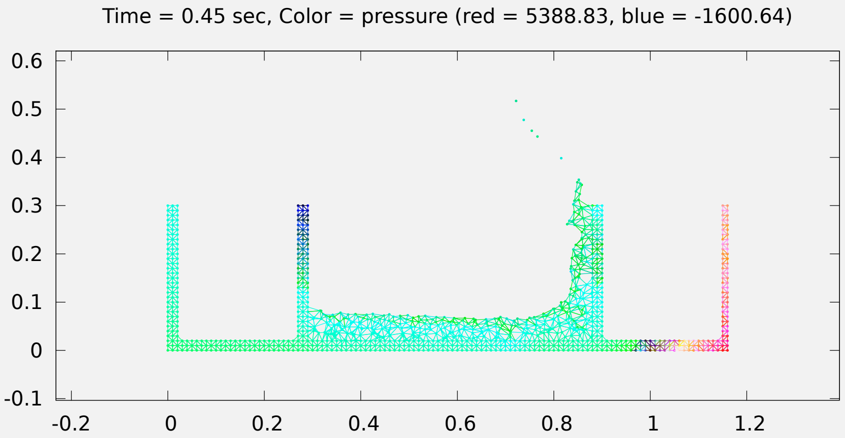

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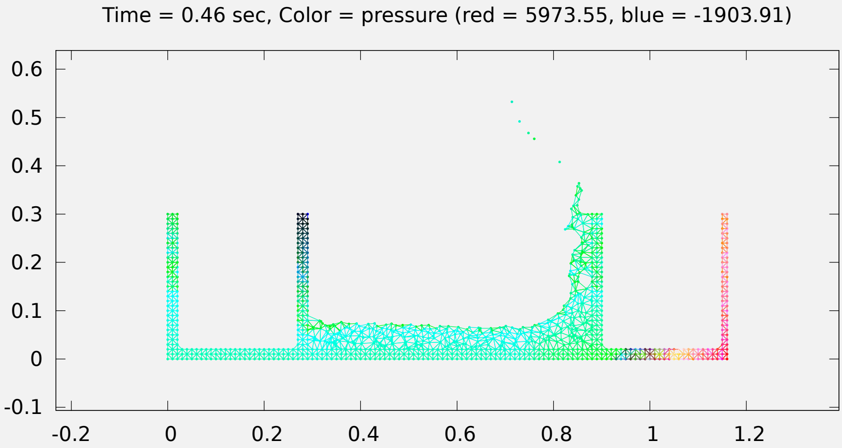

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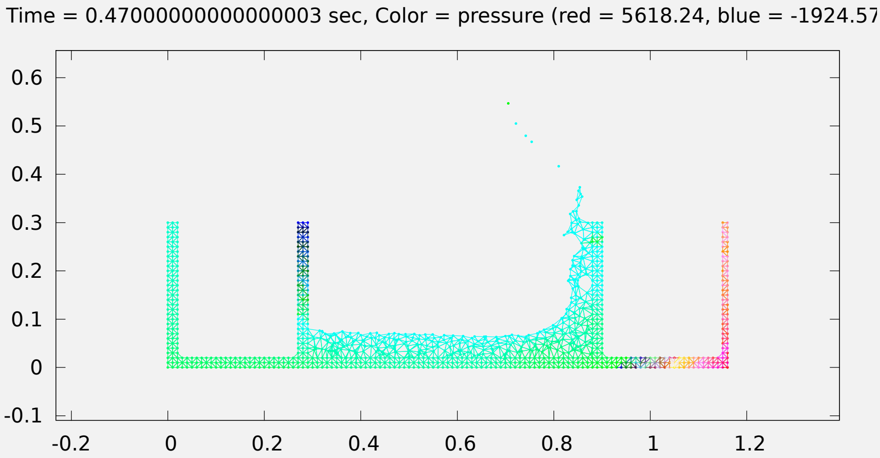

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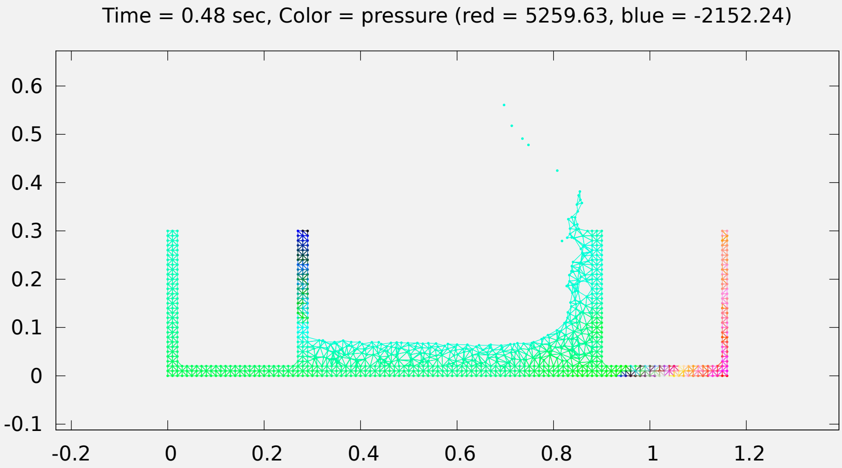

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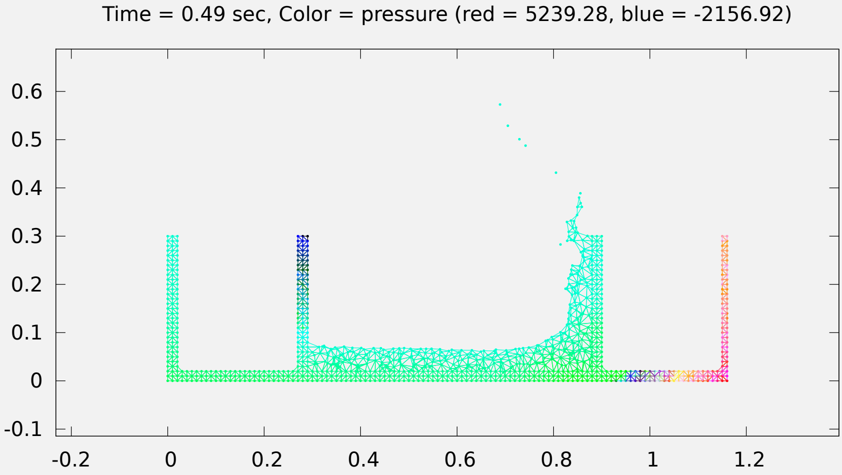

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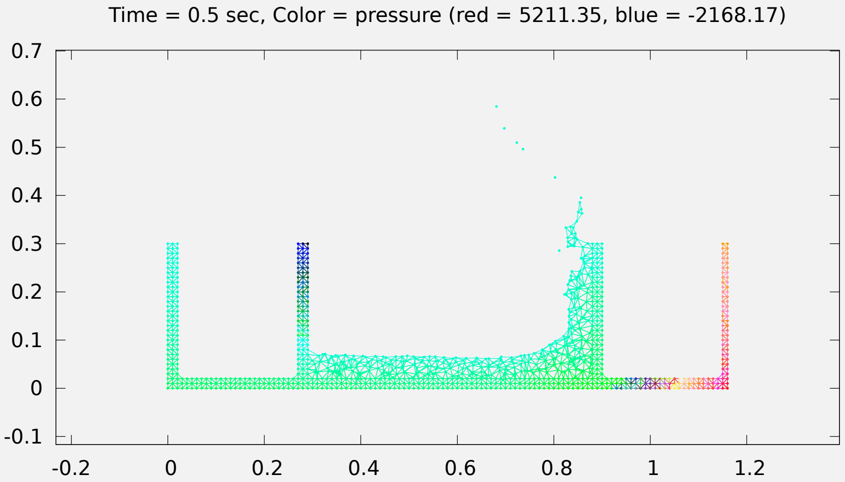
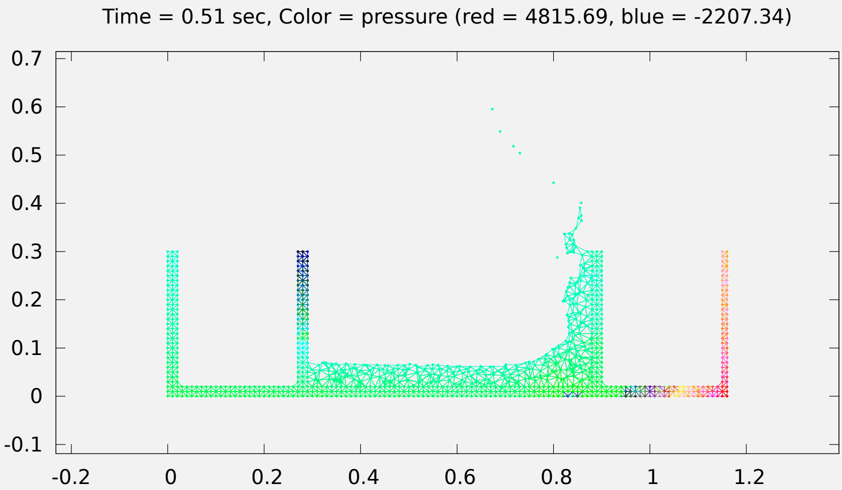


Water column collapse : pressure distribution



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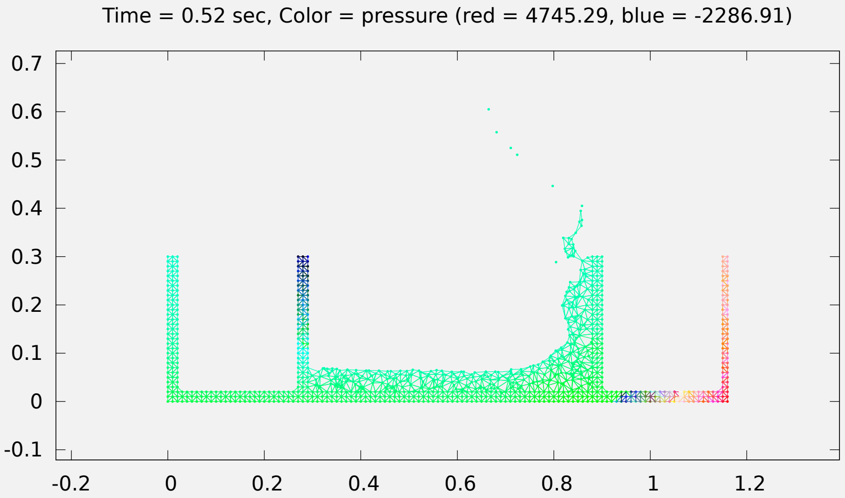

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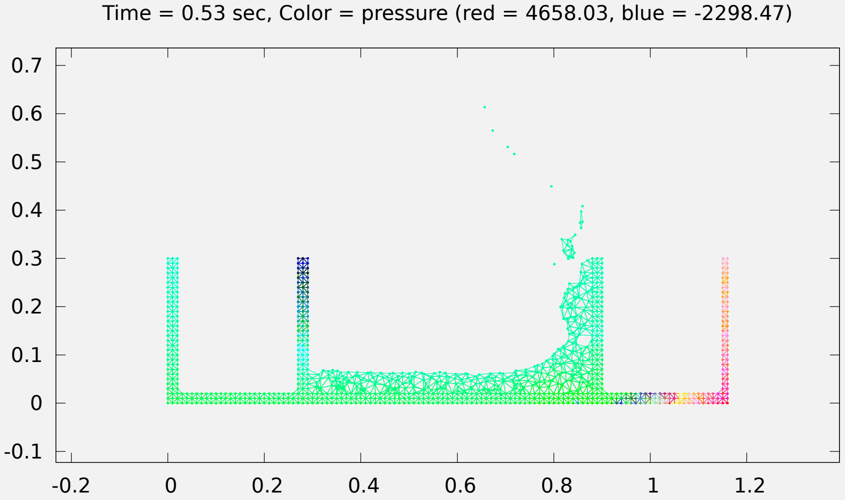

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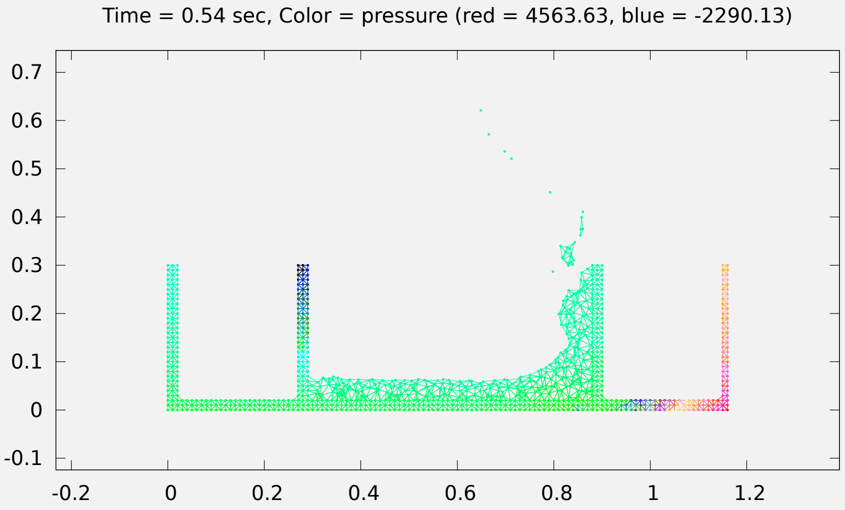

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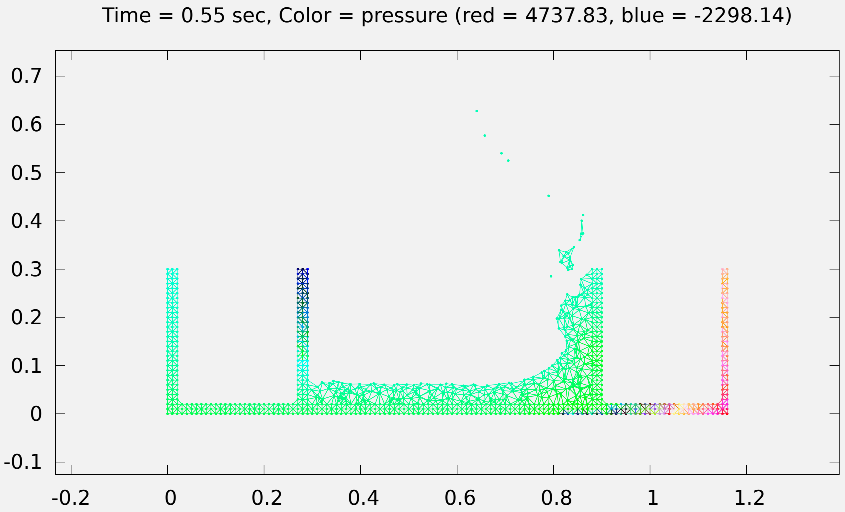

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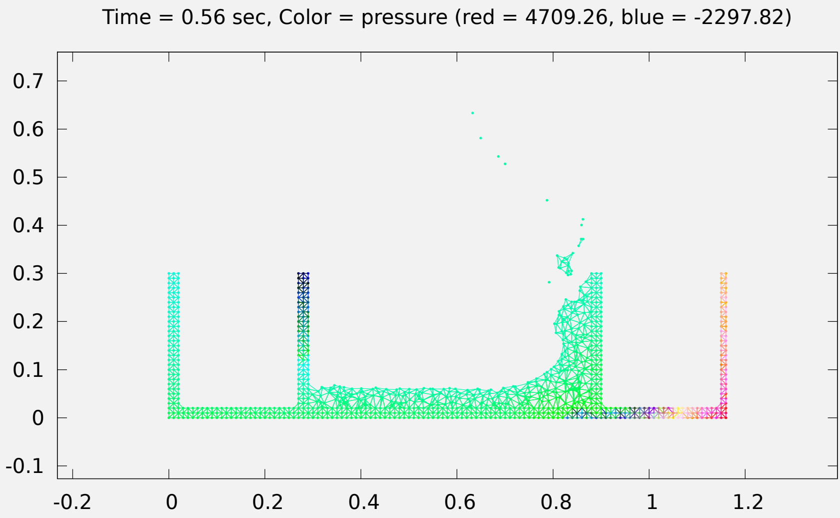

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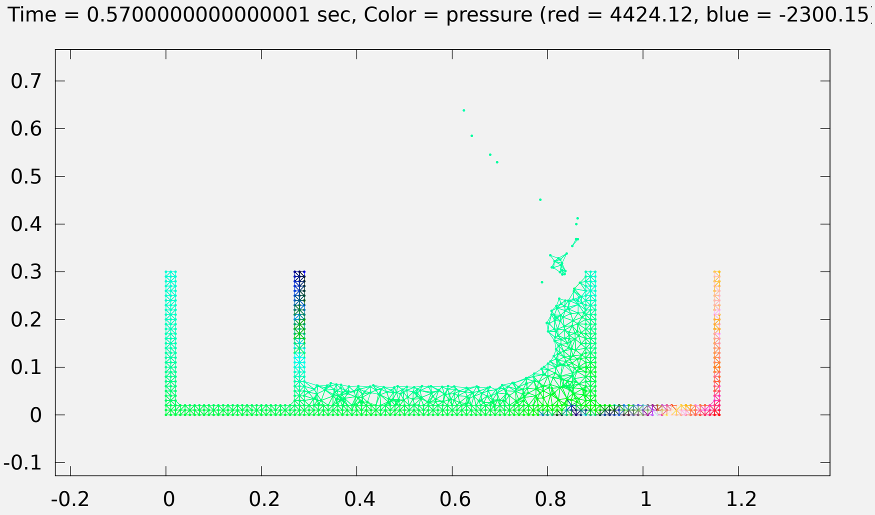

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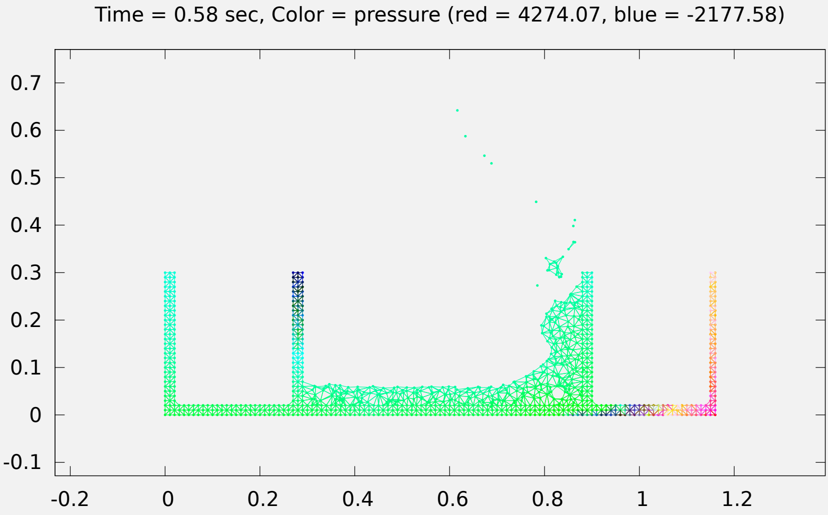

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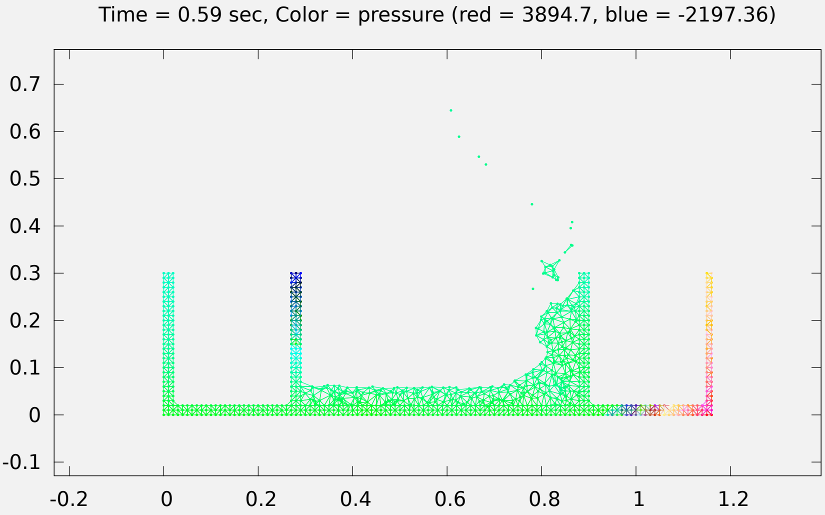

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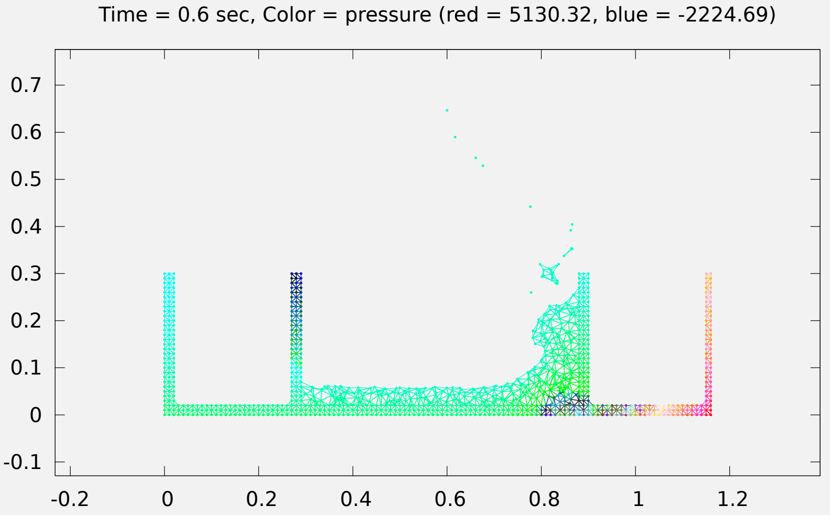

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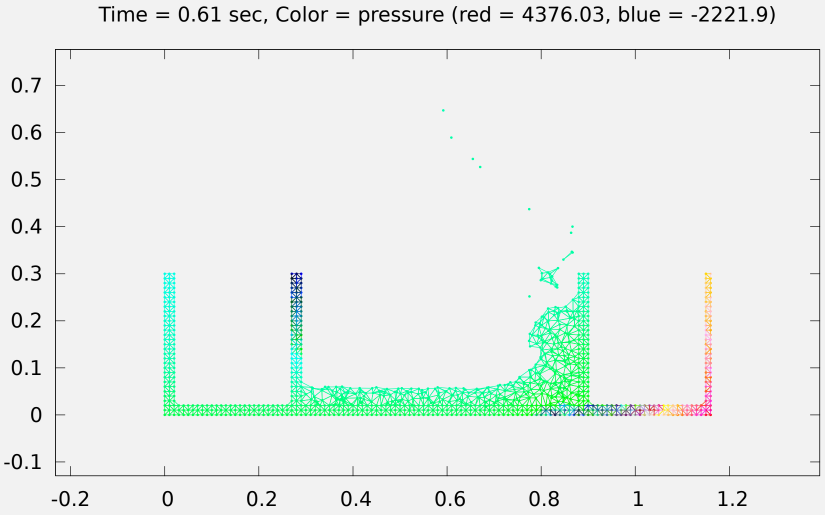

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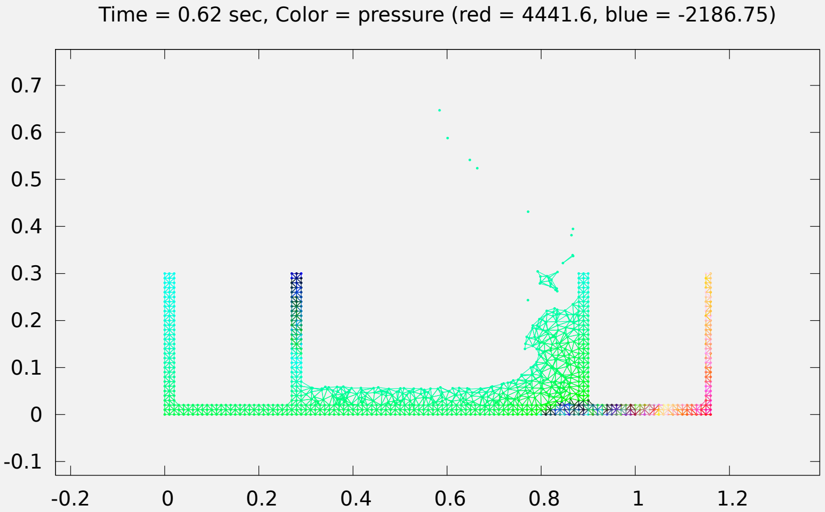

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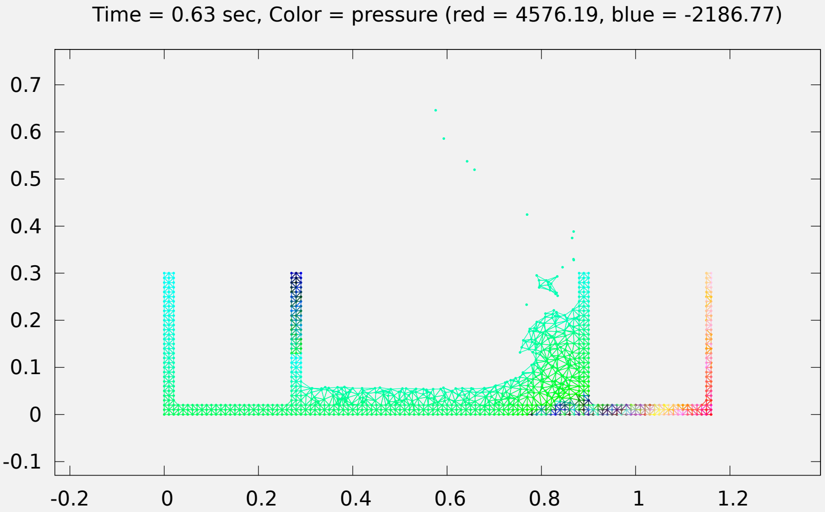

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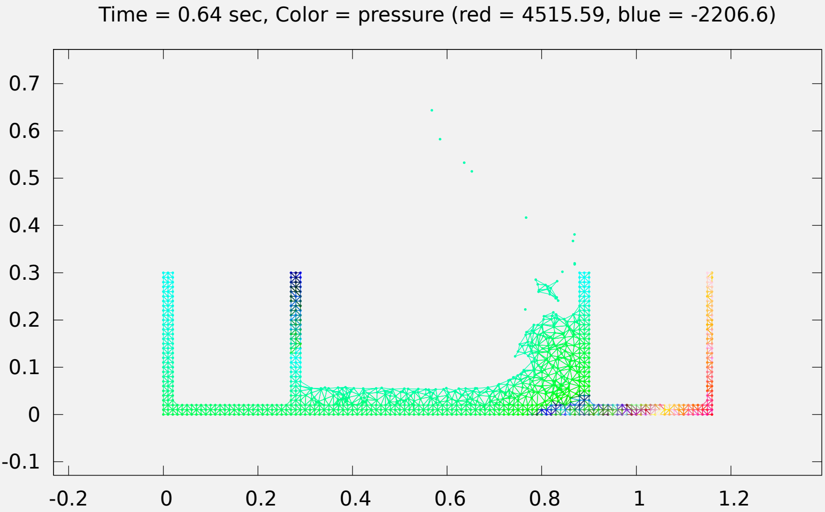

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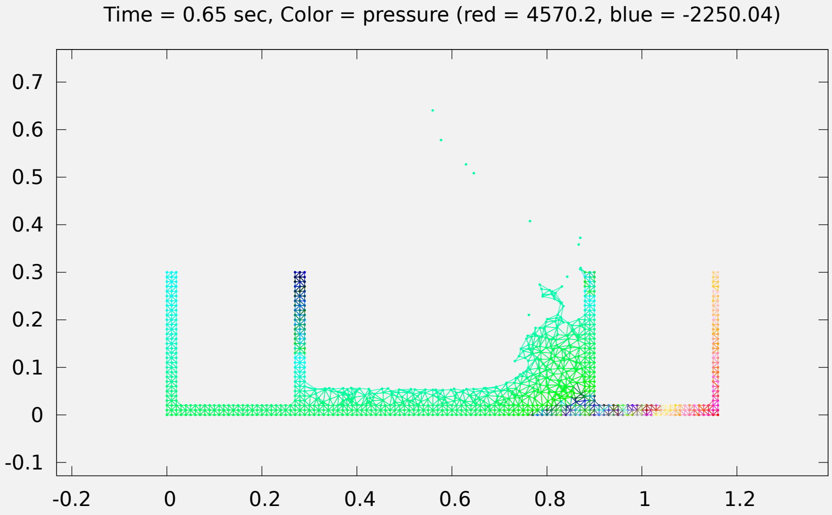

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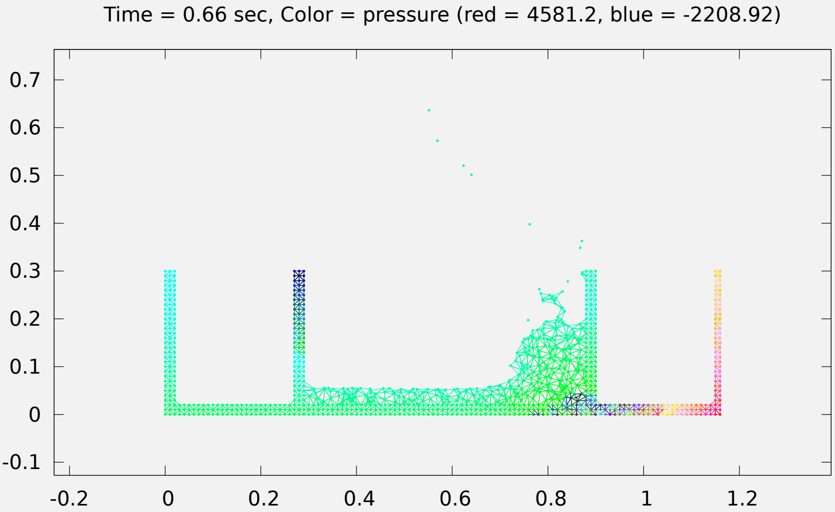

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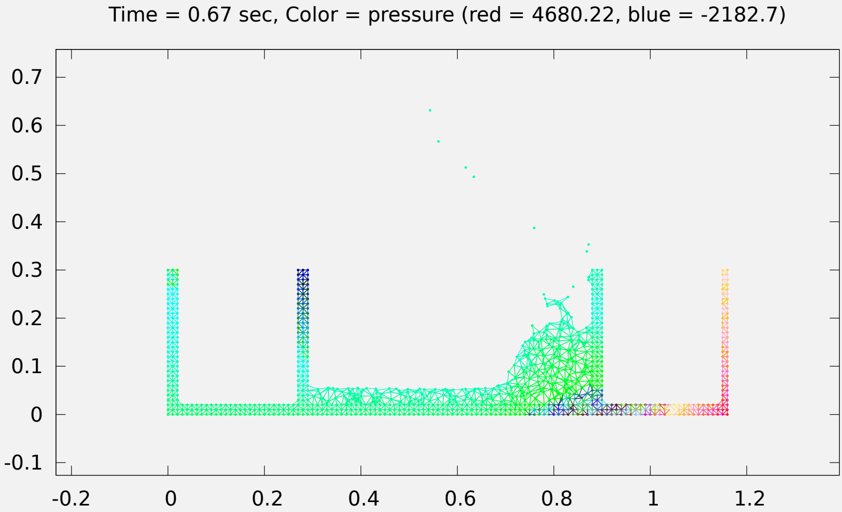

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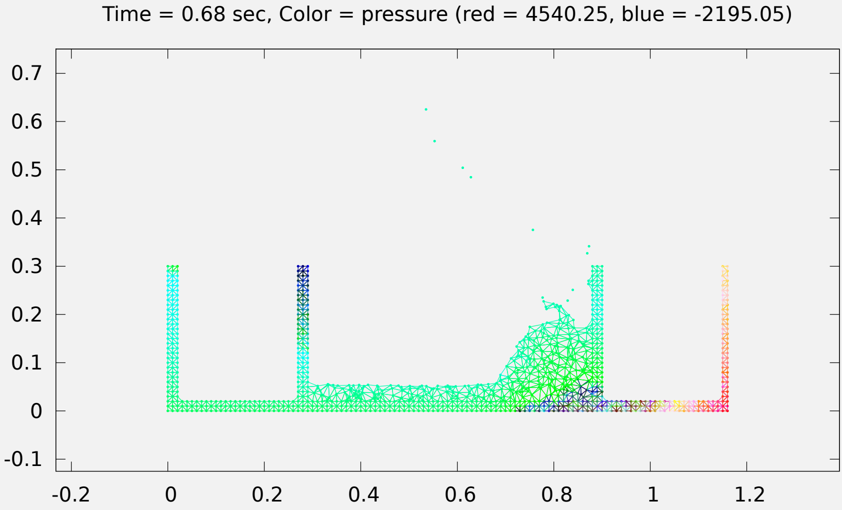

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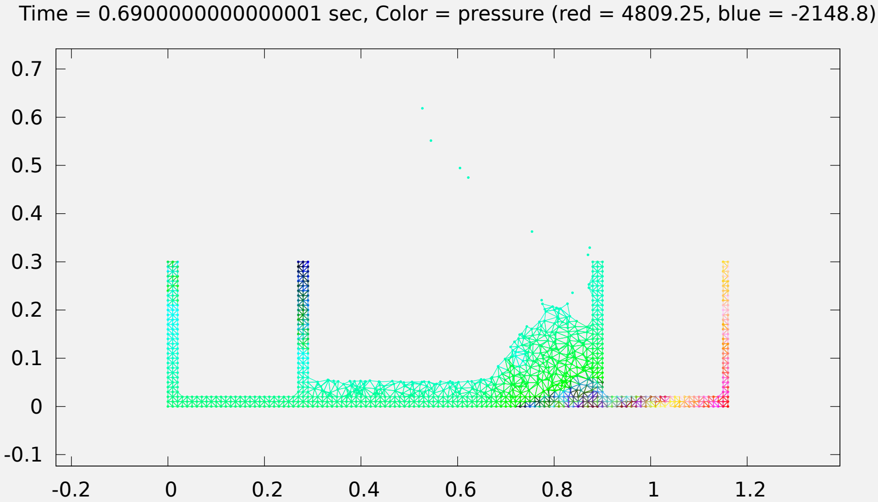

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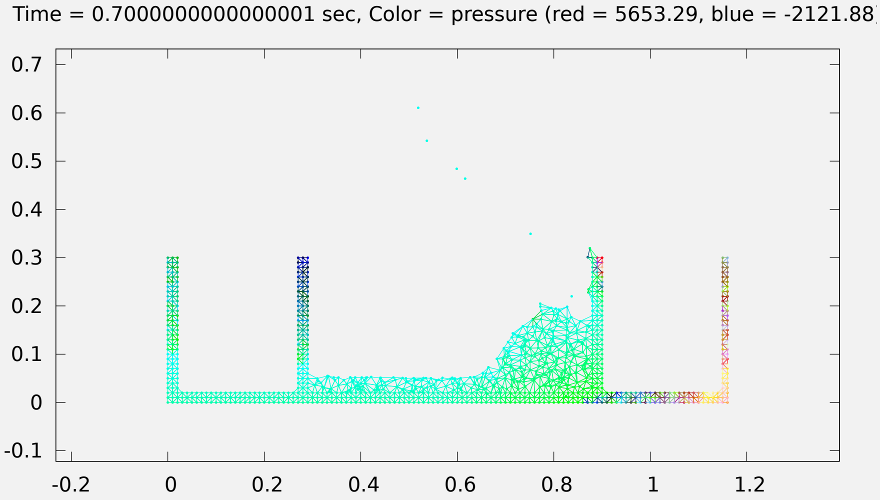

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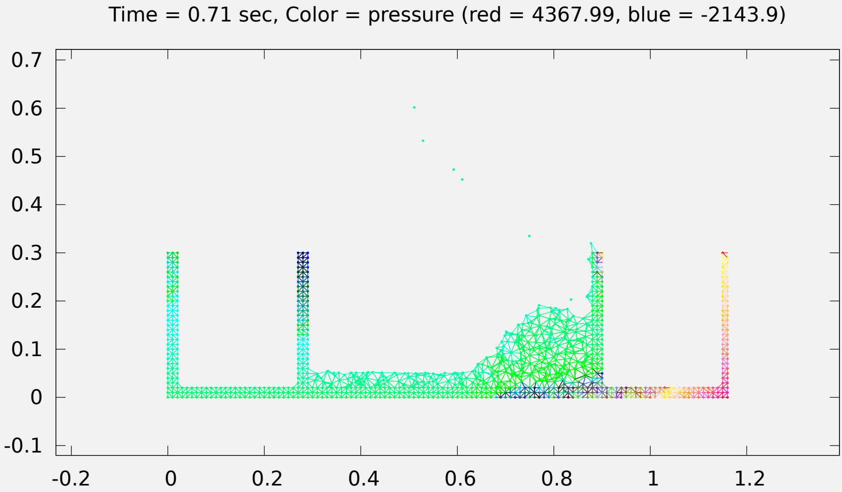

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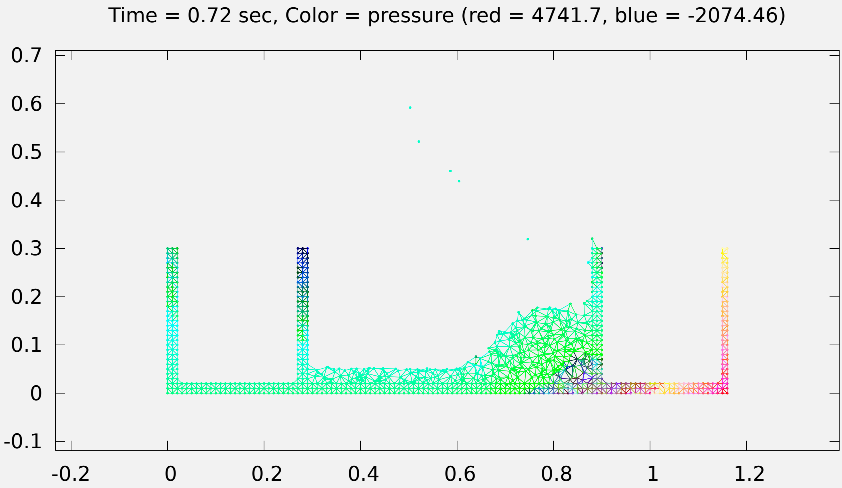

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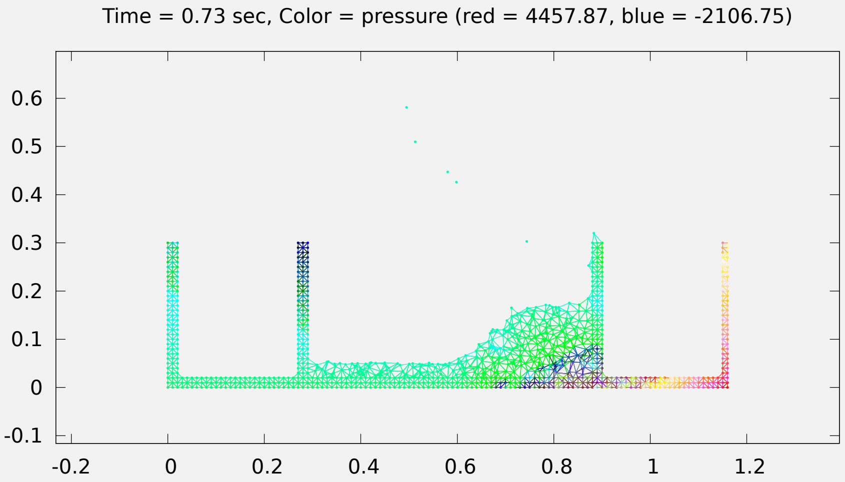

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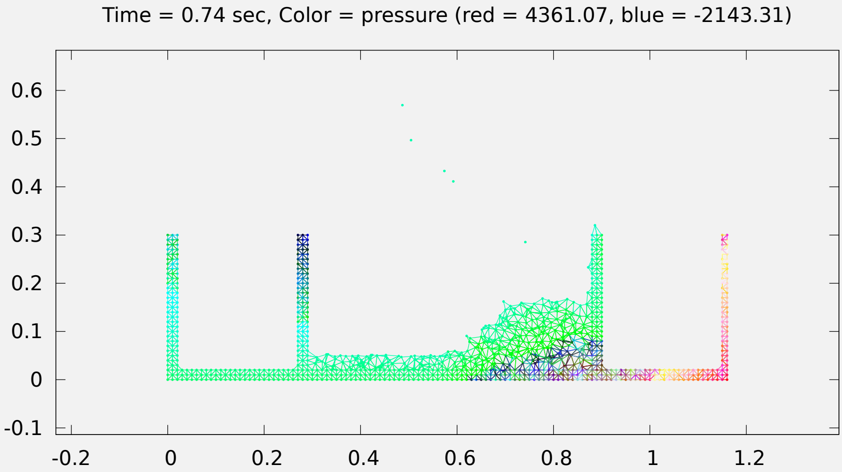

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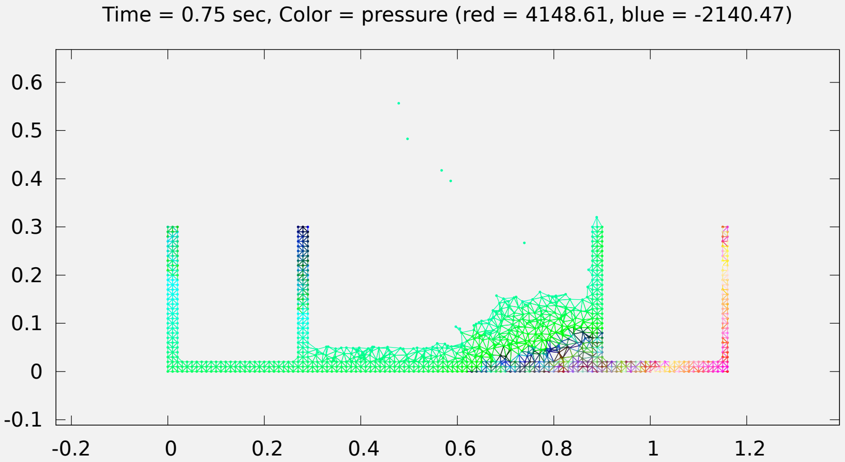

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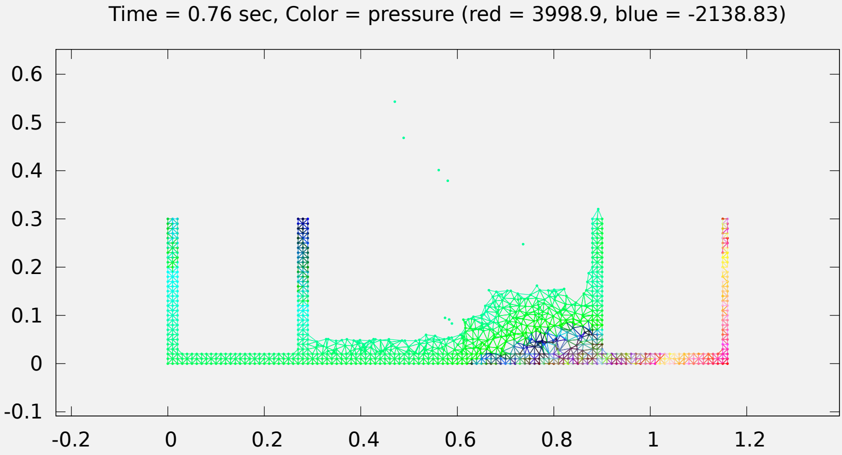

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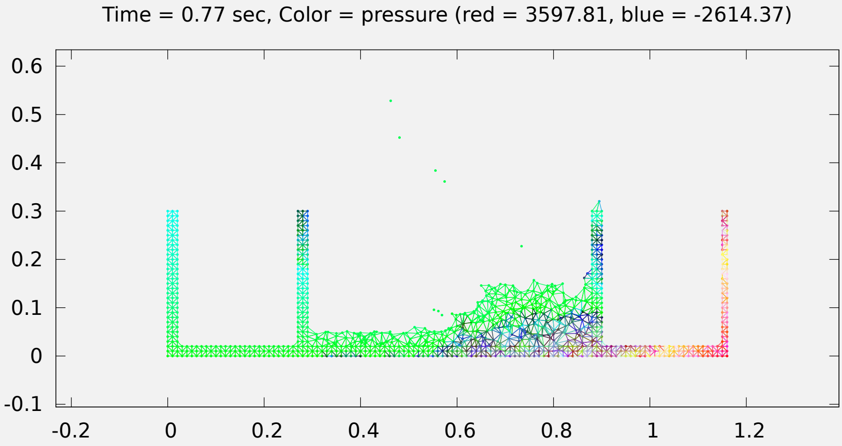

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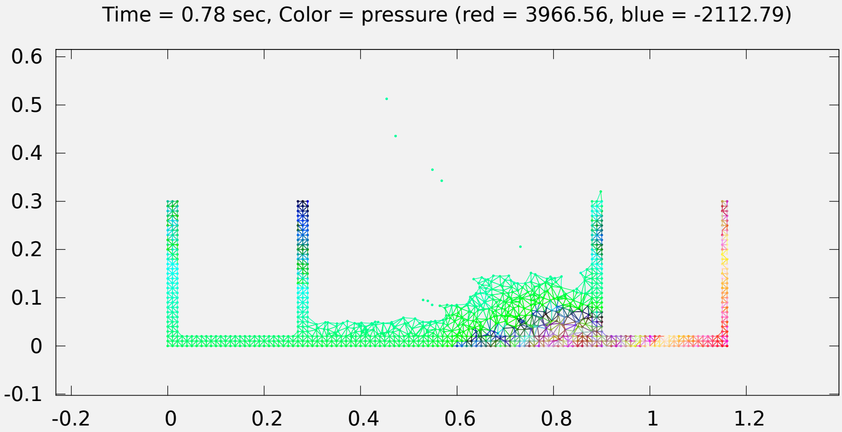

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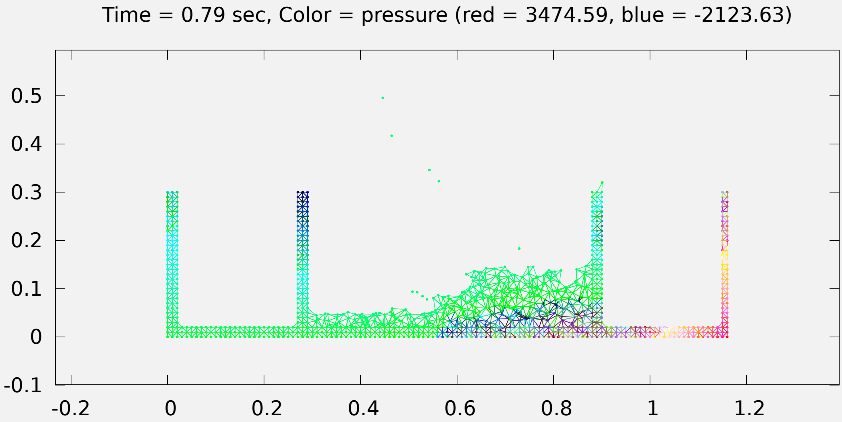

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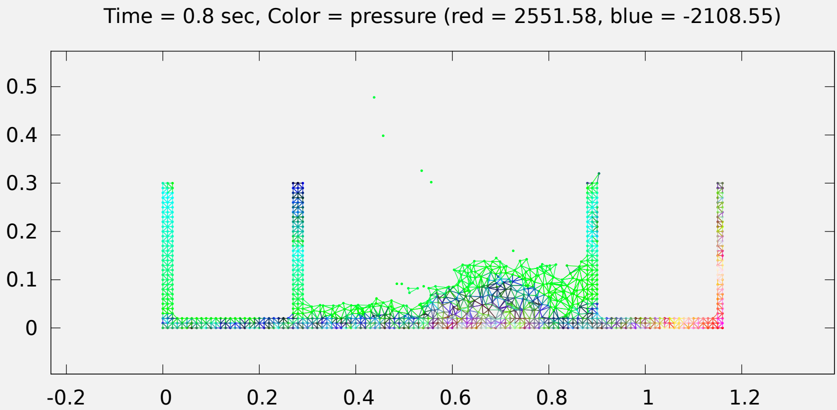

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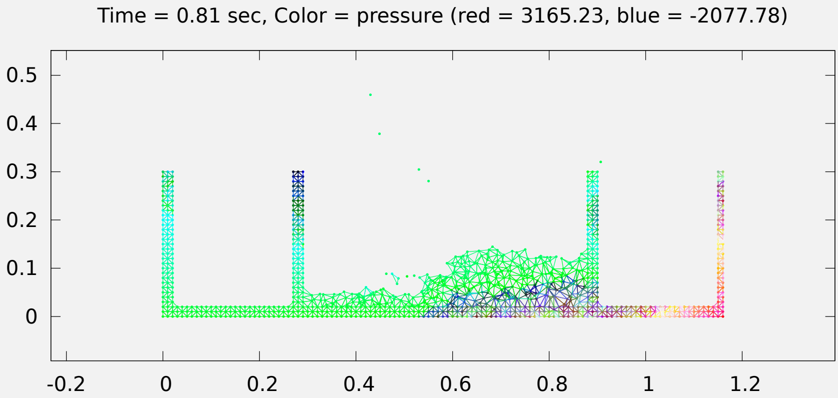

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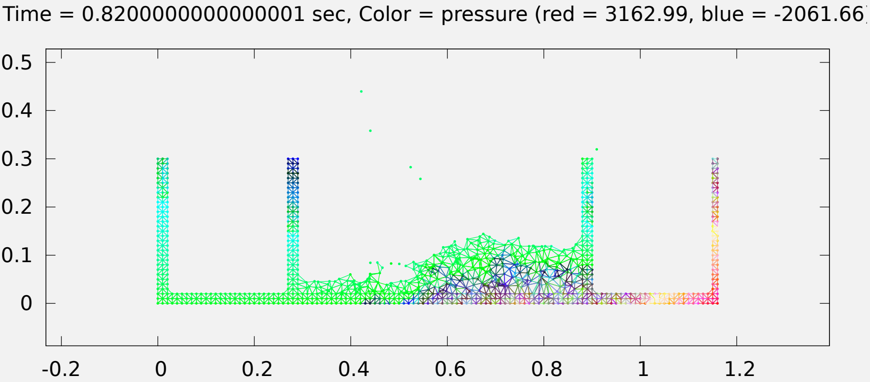

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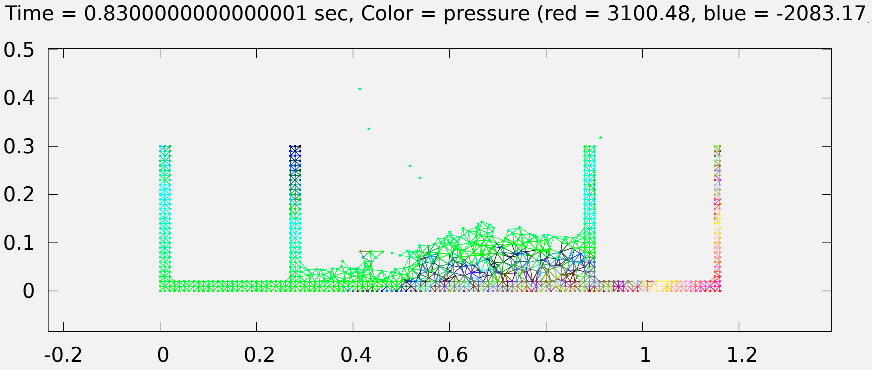

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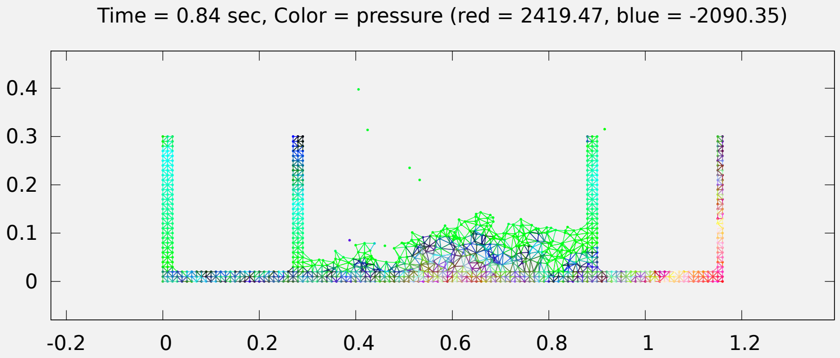

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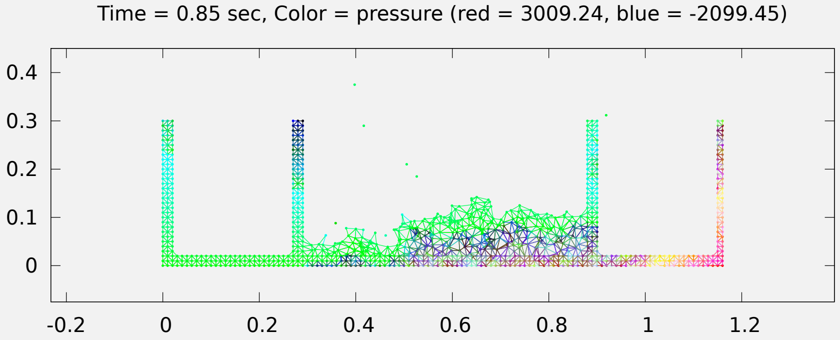

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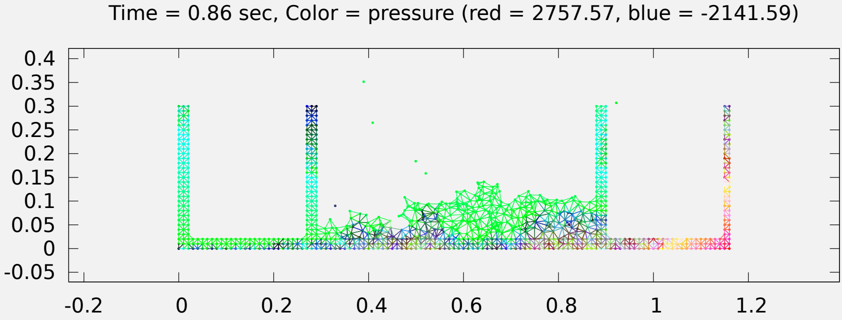

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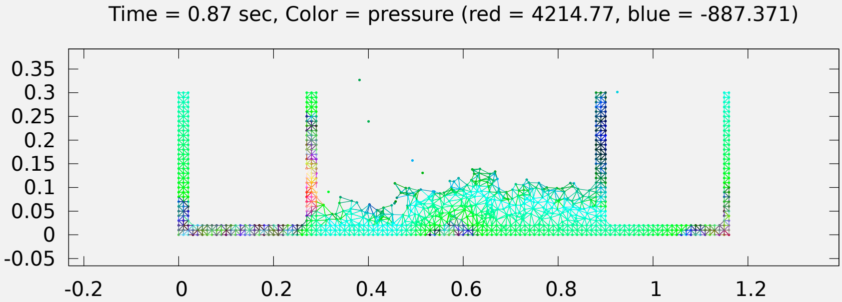

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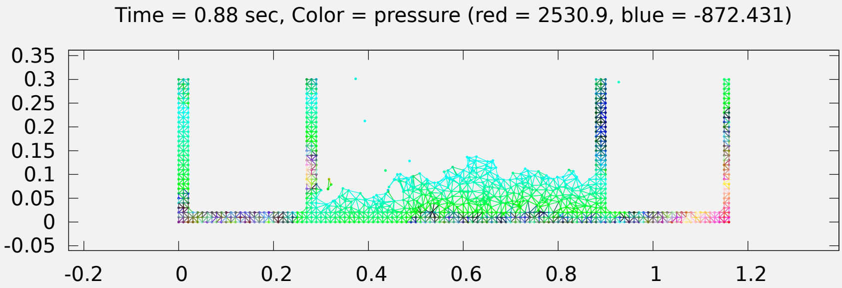

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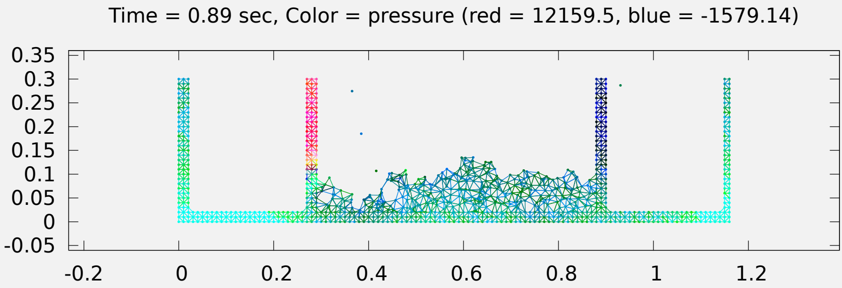

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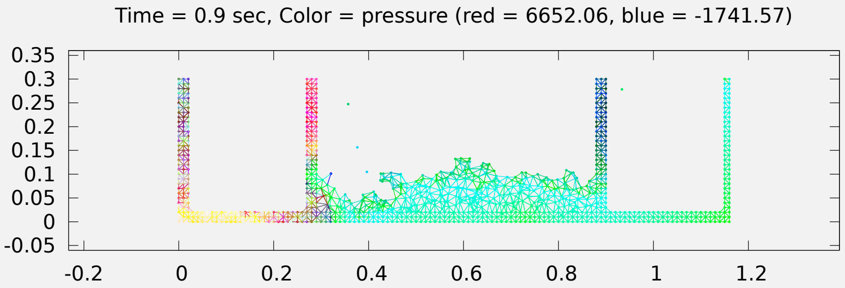

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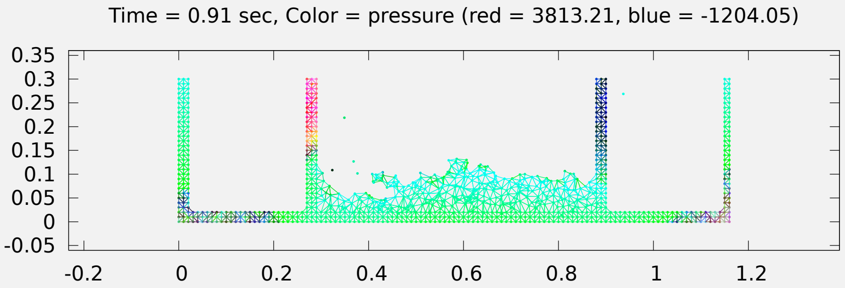

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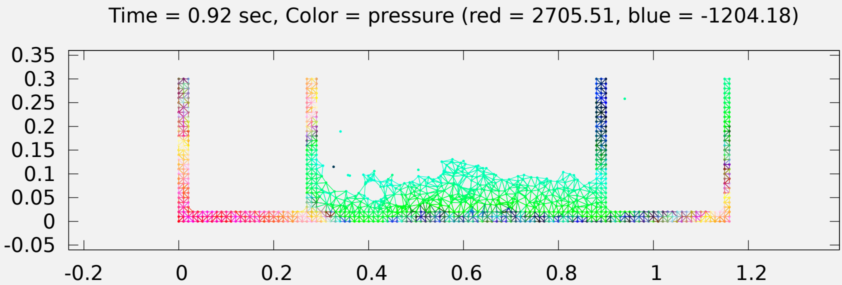

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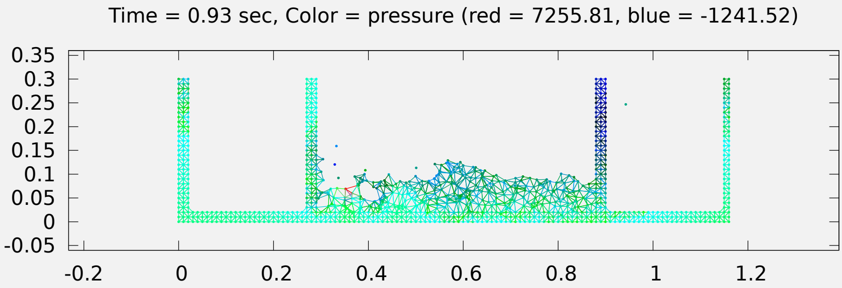

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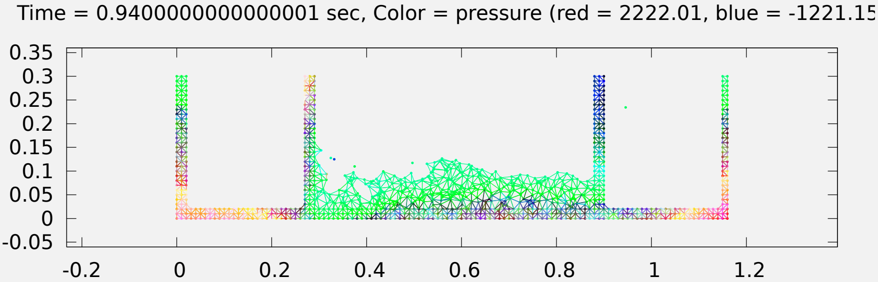

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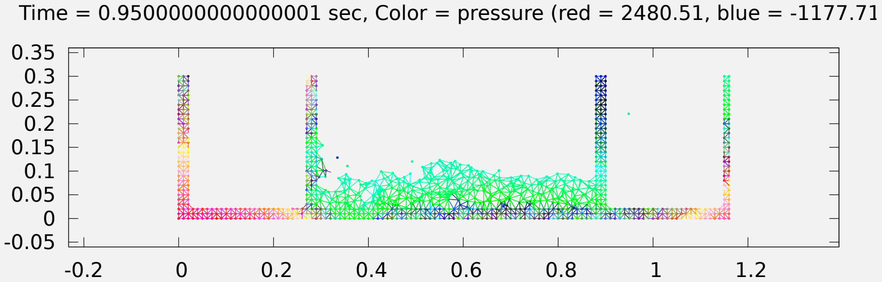

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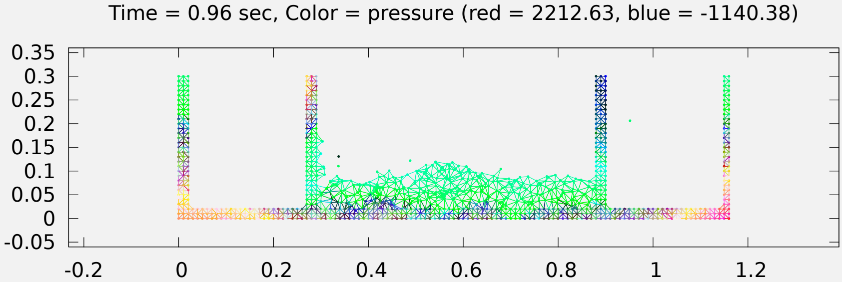

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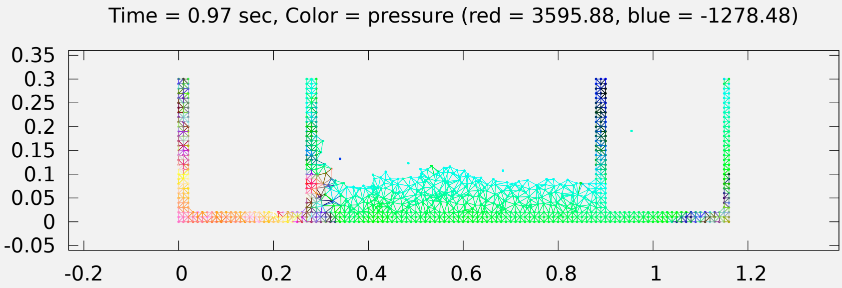

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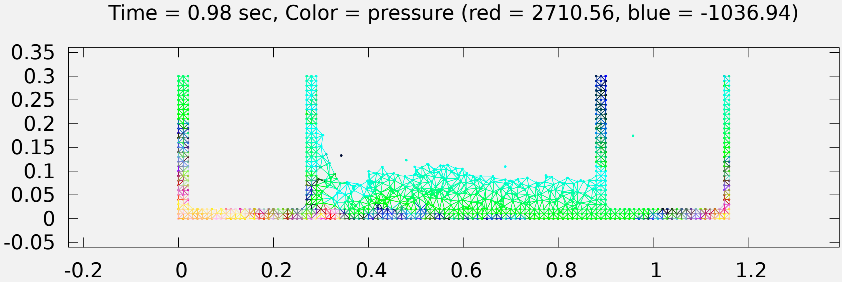

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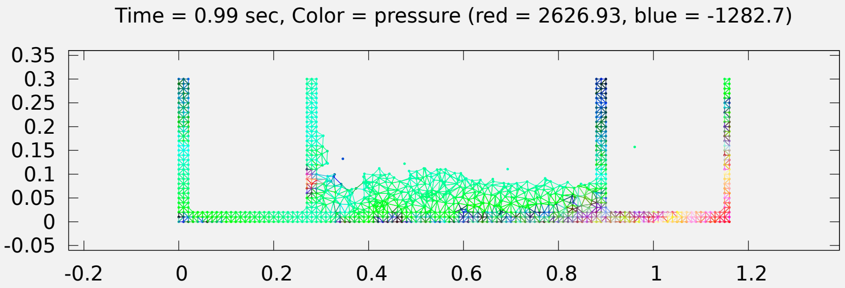

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- Alpha Shape is a generalization of the convex hull of a set of nodes. Let α a real number with $0 \leq \alpha \leq \infty$. For $\alpha = \infty$, the Alpha Shape is identical to the Delaunay Triangulation. For $\alpha = 0$, the Alpha Shape shrinks to the set of nodes. Setting α to a appropriate value can remove the unnecessary triangles to recover the real boundaries.

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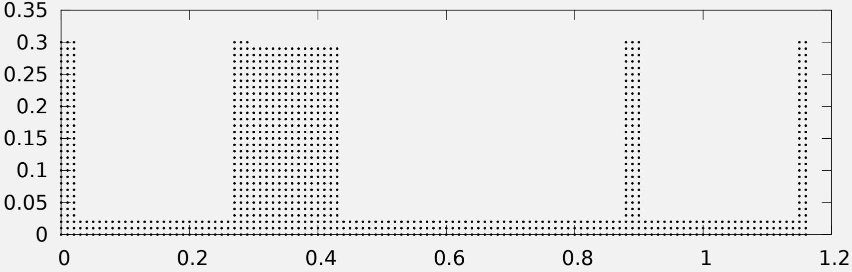
- Remaining triangles are elements to be created in OpenSees.

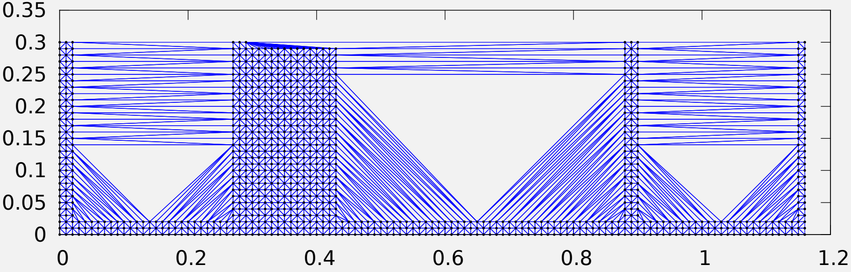
Example of meshing

At each time step, a set of nodes are given



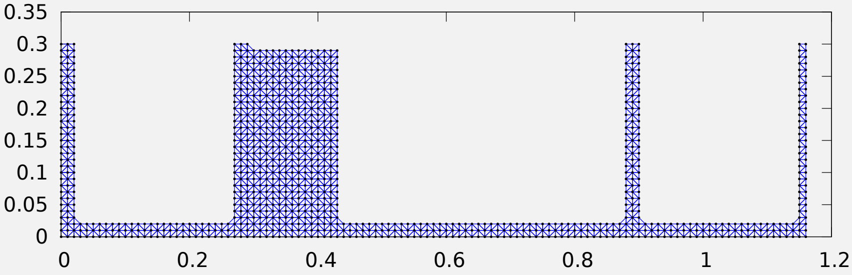
Example of meshing

Delaunay Triangulation of the set of nodes is calculated



Example of meshing

Alpha Shape of the set of nodes ($\alpha = 1.4$) is calculated



Outline

Sensitivity

Definition

The effects of assumed parameter values on computed response

Sensitivity

Subsequent applications of sensitivity include

- Reliability analysis
  - Quantify system performance under multiple limit state
- Optimization
  - Find best solution for some objective functions and constraints on the system
- System identification
  - Inverse modeling, find model parameters that match observed results
- and others ...

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- θ – modeling or physical property

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- A simple way (Finite Difference Method)

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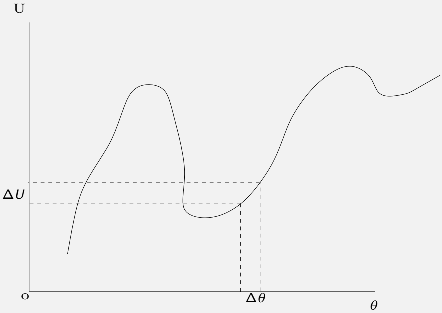

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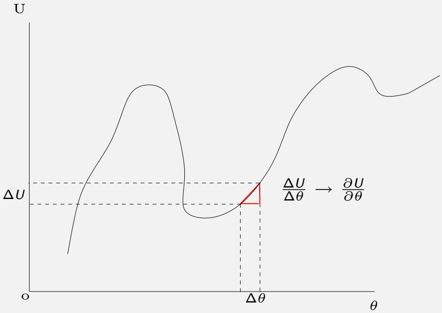

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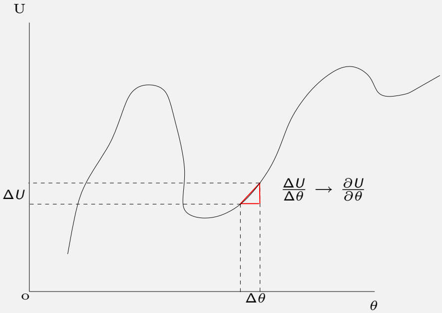

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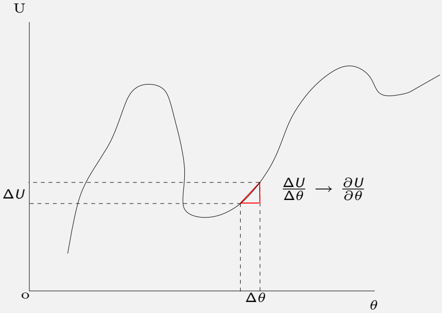

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FDM is not practical due to the computational cost

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$$\mathbf{M}\frac{\partial \dot{\mathbf{U}}}{\partial \theta} + \mathbf{K}\frac{\partial \mathbf{U}}{\partial \theta} = \frac{\partial \mathbf{F}}{\partial \theta} - \frac{\partial \mathbf{M}}{\partial \theta}\dot{\mathbf{U}} - \frac{\partial \mathbf{K}}{\partial \theta}\mathbf{U}$$

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- A direct way (Direct Differentiation Method – DDM)

$$\mathbf{M}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} = \mathbf{F}$$

$$\frac{\partial \mathbf{M}}{\partial \theta}\dot{\mathbf{U}} + \mathbf{M}\frac{\partial \dot{\mathbf{U}}}{\partial \theta} + \frac{\partial \mathbf{K}}{\partial \theta}\mathbf{U} + \mathbf{K}\frac{\partial \mathbf{U}}{\partial \theta} = \frac{\partial \mathbf{F}}{\partial \theta}$$

$$\mathbf{M}\frac{\partial \dot{\mathbf{U}}}{\partial \theta} + \mathbf{K}\frac{\partial \mathbf{U}}{\partial \theta} = \frac{\partial \mathbf{F}}{\partial \theta} - \frac{\partial \mathbf{M}}{\partial \theta}\dot{\mathbf{U}} - \frac{\partial \mathbf{K}}{\partial \theta}\mathbf{U}$$

Computing sensitivity

- A direct way (Direct Differentiation Method – DDM)

$$\mathbf{M}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} = \mathbf{F}$$

$$\frac{\partial \mathbf{M}}{\partial \theta}\dot{\mathbf{U}} + \mathbf{M}\frac{\partial \dot{\mathbf{U}}}{\partial \theta} + \frac{\partial \mathbf{K}}{\partial \theta}\mathbf{U} + \mathbf{K}\frac{\partial \mathbf{U}}{\partial \theta} = \frac{\partial \mathbf{F}}{\partial \theta}$$

$$\mathbf{M}\frac{\partial \dot{\mathbf{U}}}{\partial \theta} + \mathbf{K}\frac{\partial \mathbf{U}}{\partial \theta} = \frac{\partial \mathbf{F}}{\partial \theta} - \frac{\partial \mathbf{M}}{\partial \theta}\dot{\mathbf{U}} - \frac{\partial \mathbf{K}}{\partial \theta}\mathbf{U}$$

where,

$$\frac{\partial \mathbf{F}}{\partial \theta} - \frac{\partial \mathbf{M}}{\partial \theta}\dot{\mathbf{U}} - \frac{\partial \mathbf{K}}{\partial \theta}\mathbf{U}$$

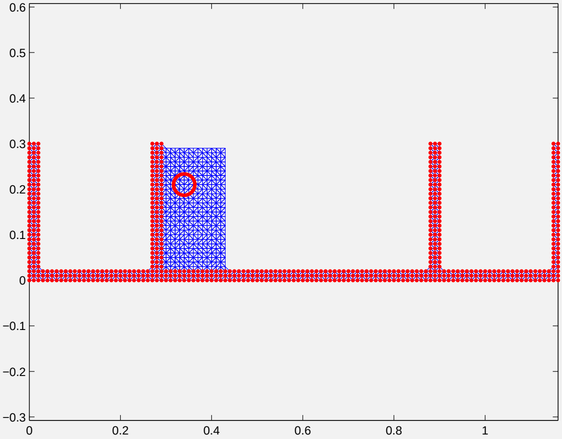
is the sensitivity "force" vector

- Only form RHS vectors and solve linear equations once for each parameter, LHS matrices don't change,
- No additional round-off error as the FDM

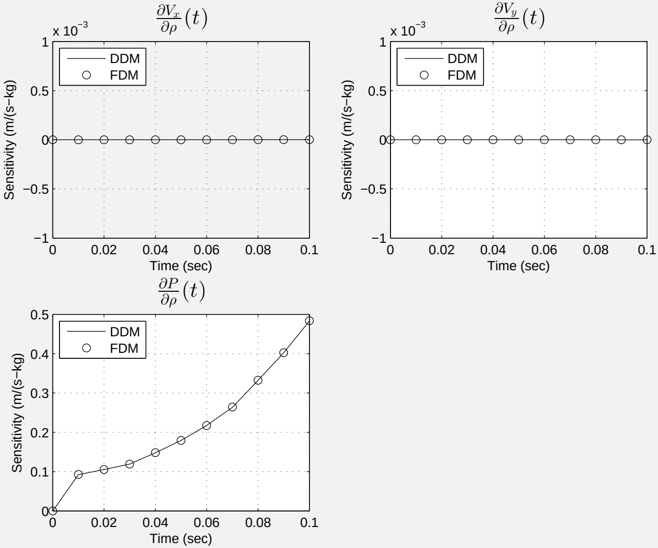
Example of sensitivity analysis

Example of sensitivity analysis

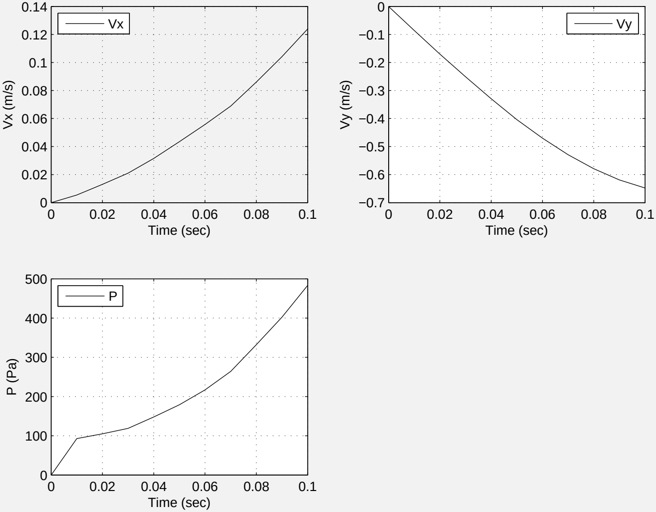
- Find $\frac{\partial V_x}{\partial \rho}(t)$, $\frac{\partial V_y}{\partial \rho}(t)$, $\frac{\partial P}{\partial \rho}(t)$ for particle 400, the sensitivity of velocities and pressure to the density of the fluid.



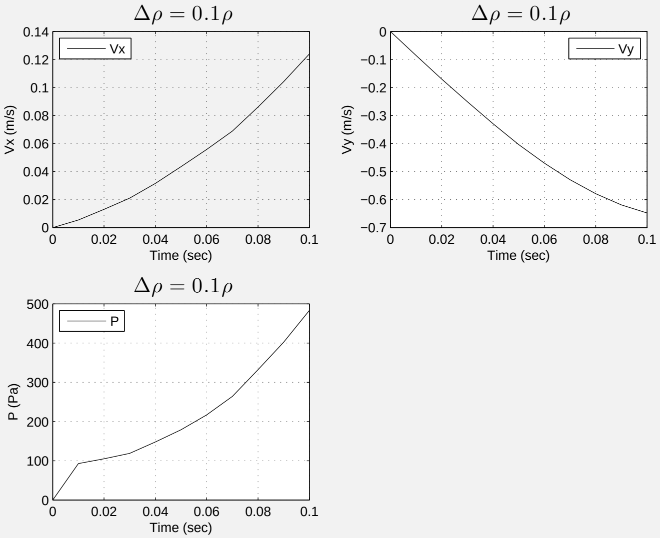
Example of sensitivity analysis



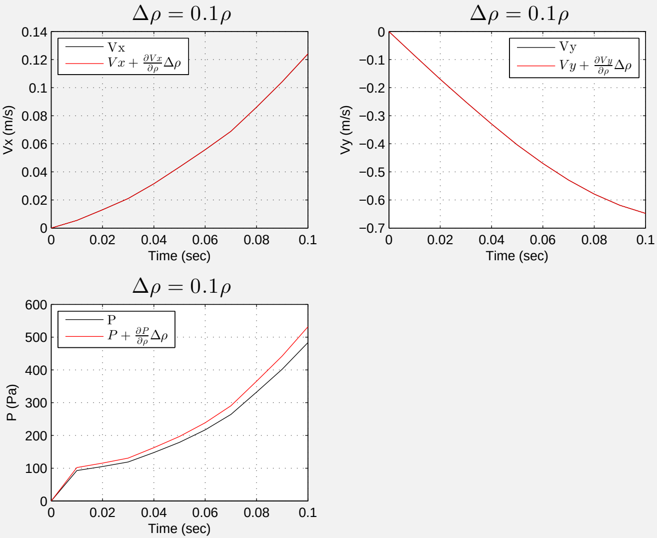
Example of sensitivity analysis



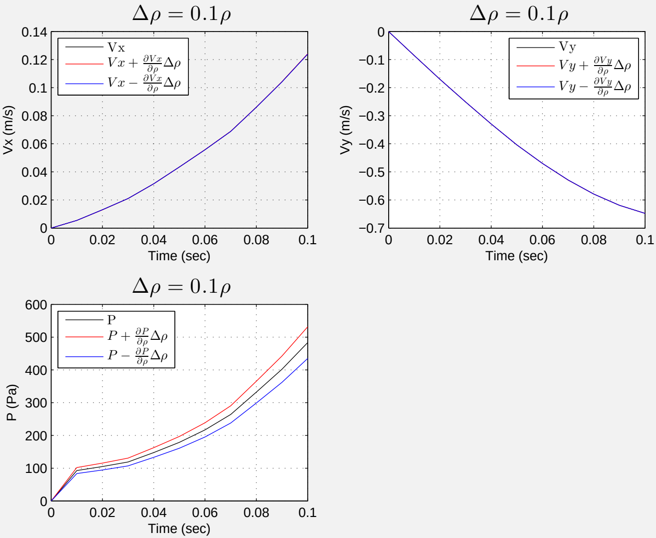
Example of sensitivity analysis



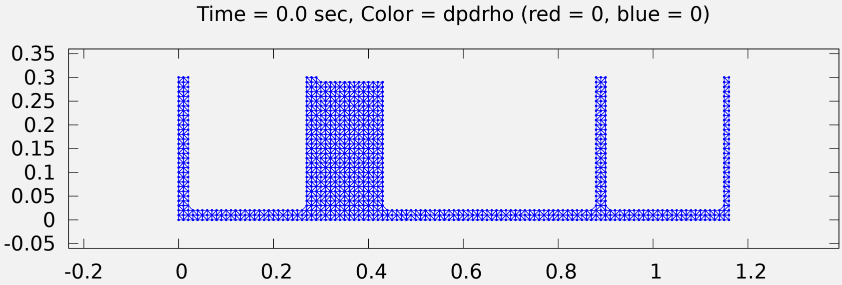
Example of sensitivity analysis



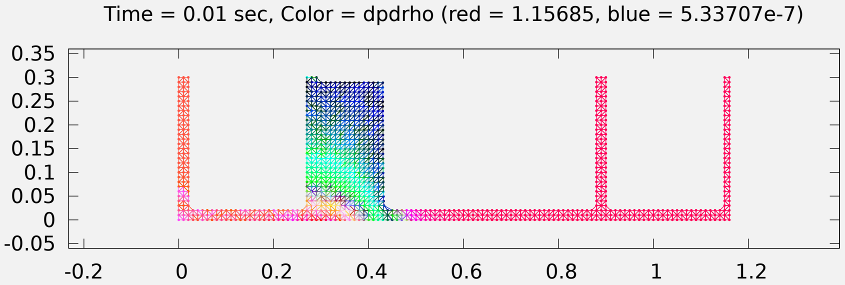
Example of sensitivity analysis



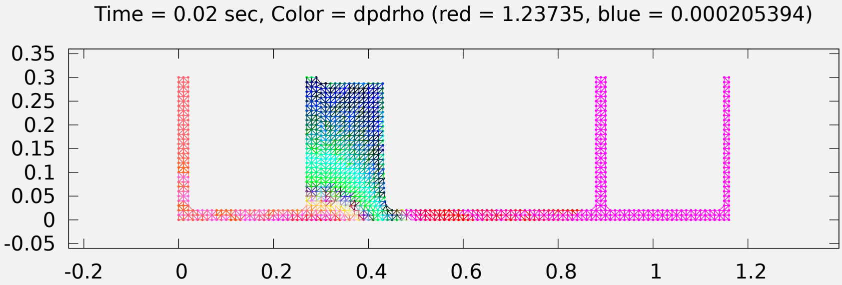
Water column collapse : pressure sensitivity distribution



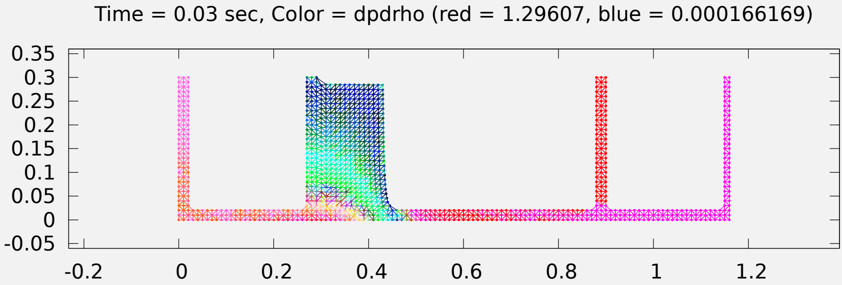
Water column collapse : pressure sensitivity distribution



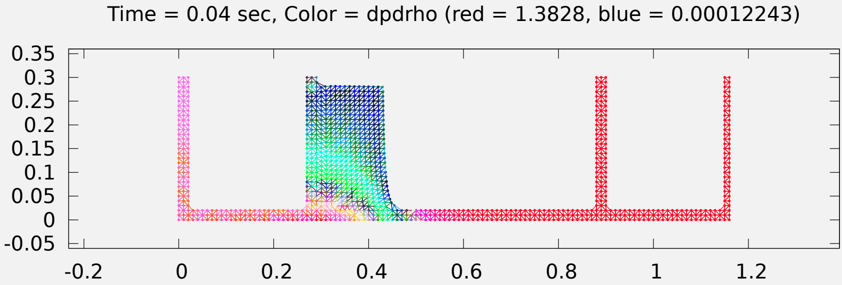
Water column collapse : pressure sensitivity distribution



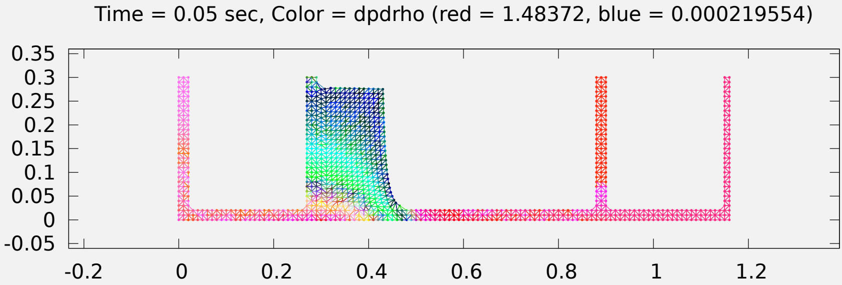
Water column collapse : pressure sensitivity distribution



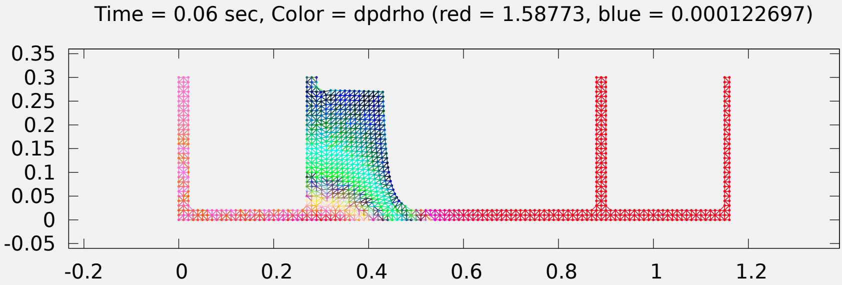
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution

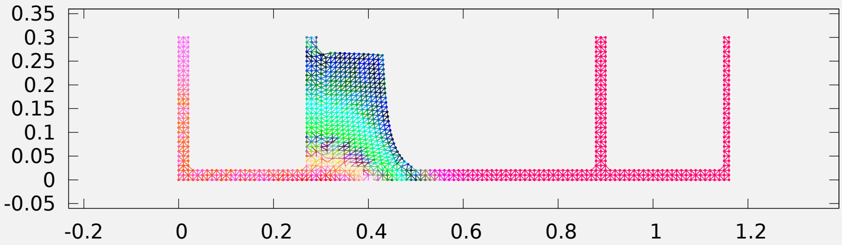


Water column collapse : pressure sensitivity distribution

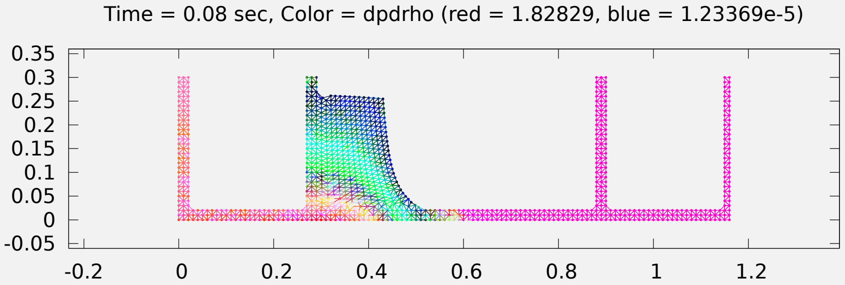


Water column collapse : pressure sensitivity distribution

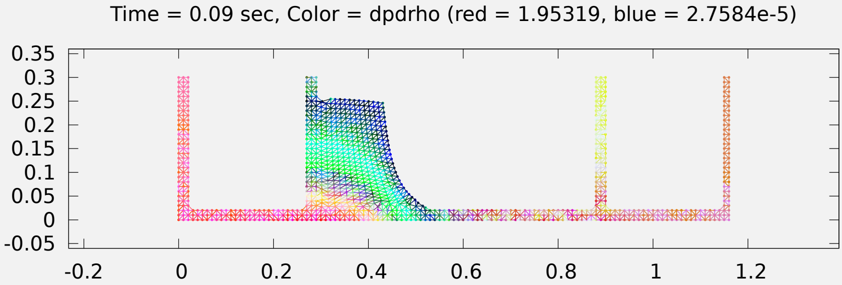
Time = 0.07 sec, Color = dpdrho (red = 1.70172, blue = 6.04305e-5)



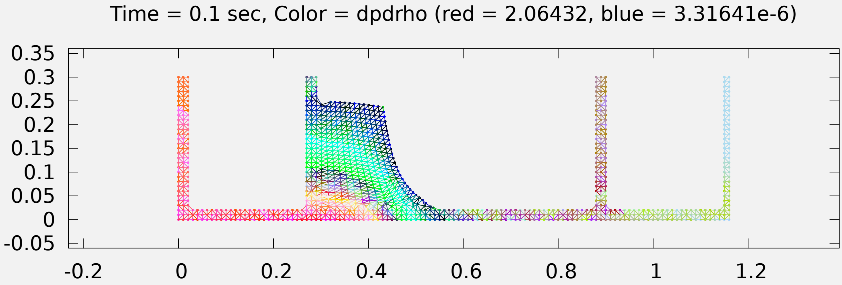
Water column collapse : pressure sensitivity distribution



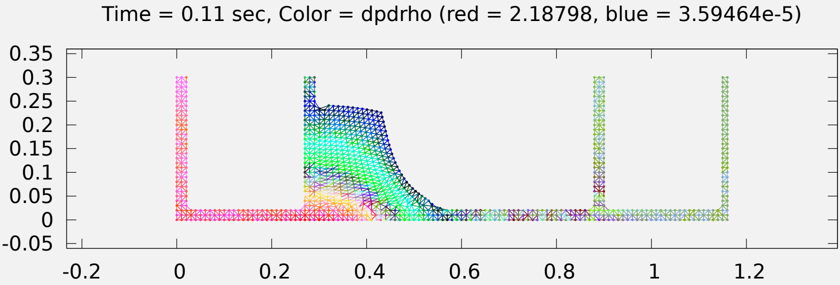
Water column collapse : pressure sensitivity distribution



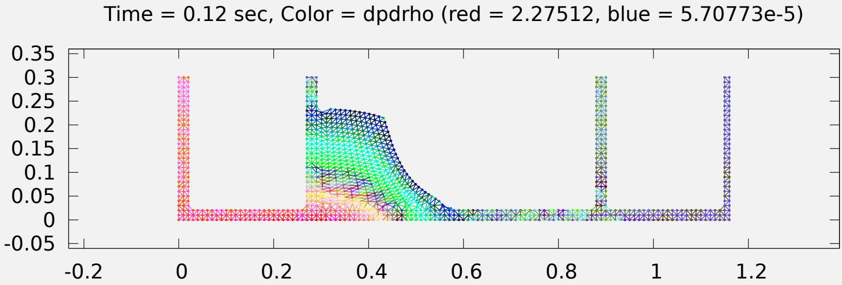
Water column collapse : pressure sensitivity distribution



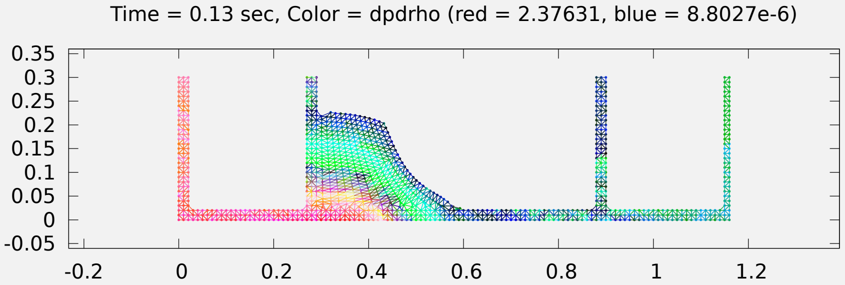
Water column collapse : pressure sensitivity distribution



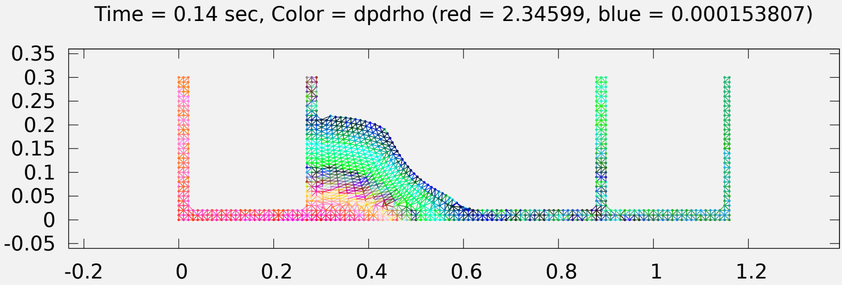
Water column collapse : pressure sensitivity distribution



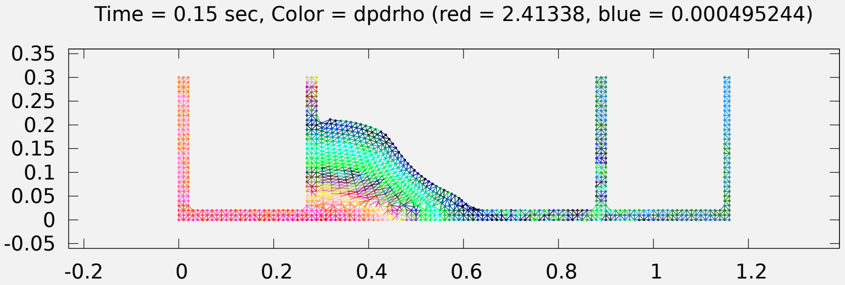
Water column collapse : pressure sensitivity distribution



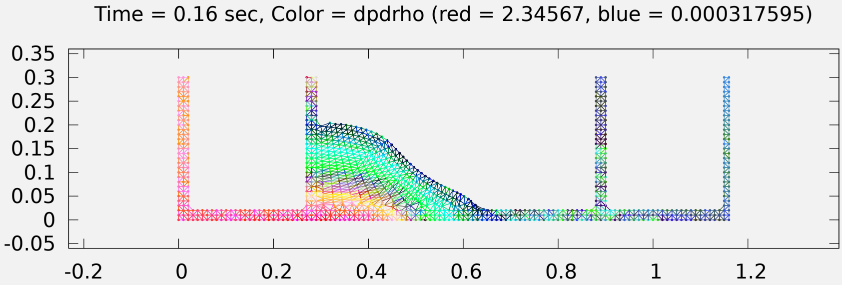
Water column collapse : pressure sensitivity distribution



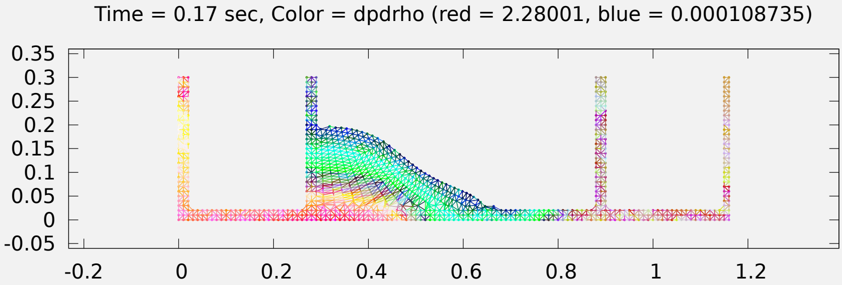
Water column collapse : pressure sensitivity distribution



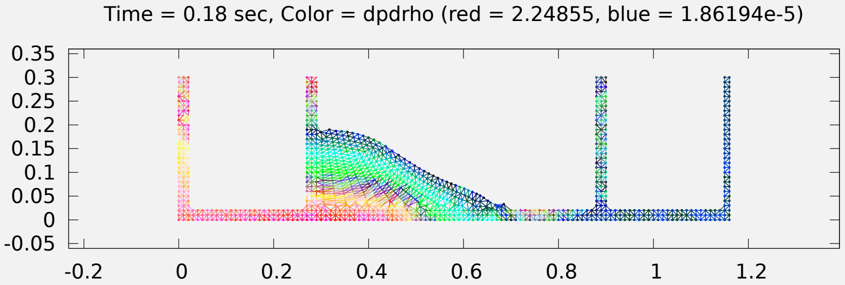
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution

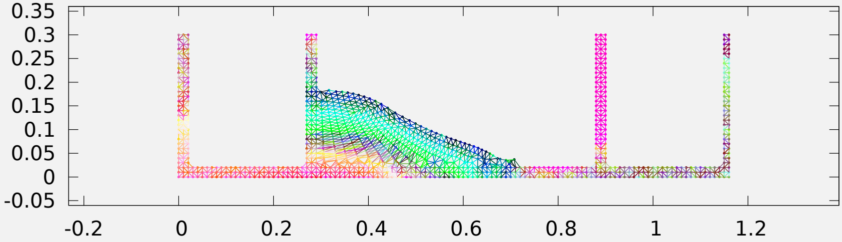


Water column collapse : pressure sensitivity distribution

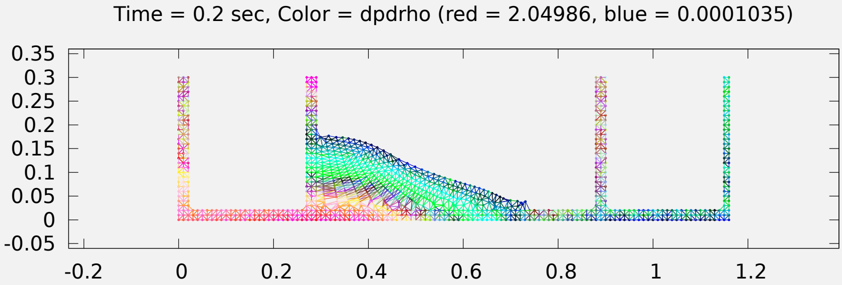


Water column collapse : pressure sensitivity distribution

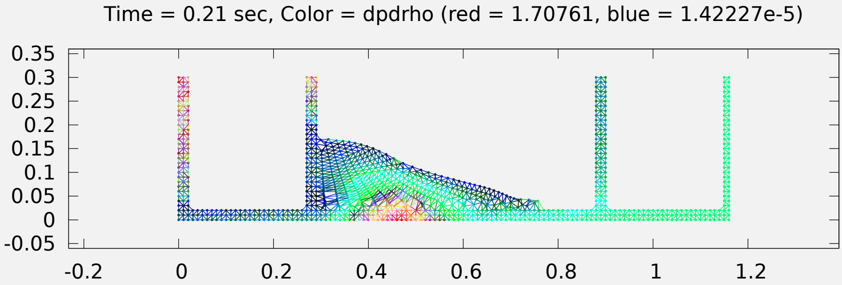
Time = 0.19 sec, Color = dpdrho (red = 2.13937, blue = 3.12969e-6)



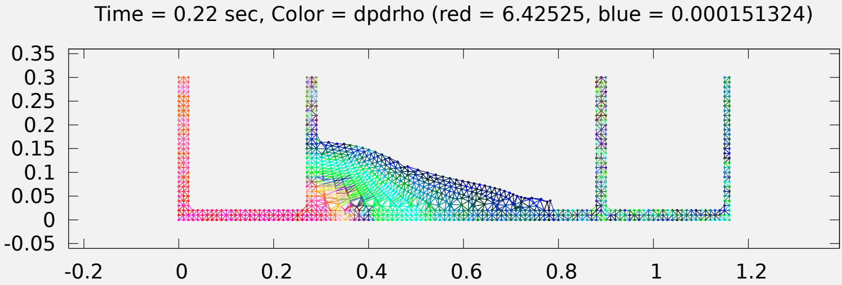
Water column collapse : pressure sensitivity distribution



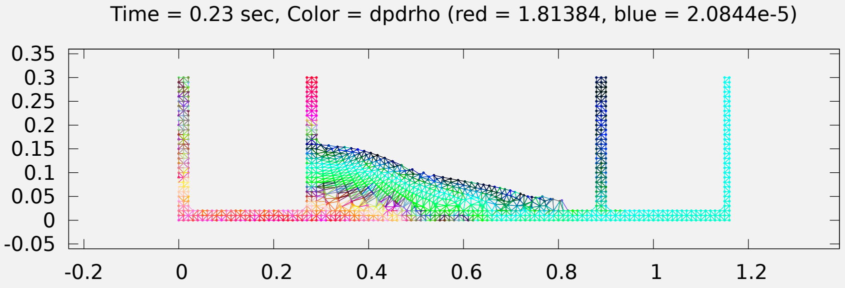
Water column collapse : pressure sensitivity distribution



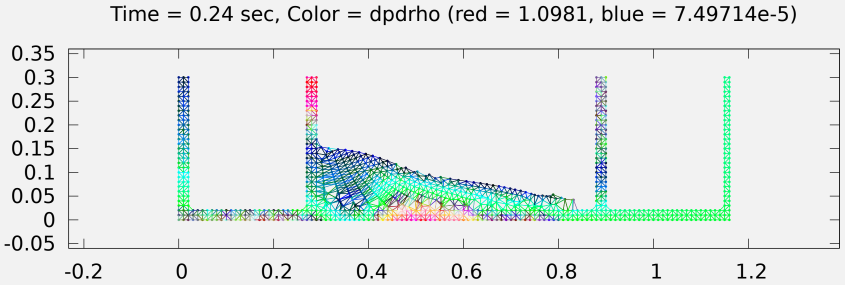
Water column collapse : pressure sensitivity distribution



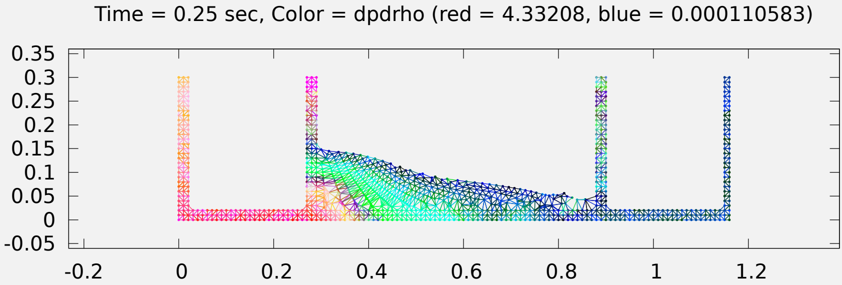
Water column collapse : pressure sensitivity distribution



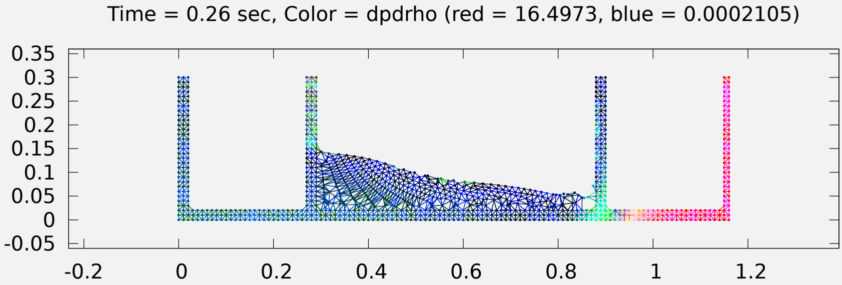
Water column collapse : pressure sensitivity distribution



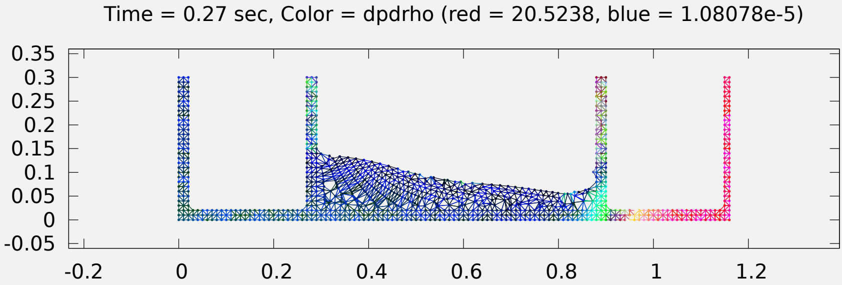
Water column collapse : pressure sensitivity distribution



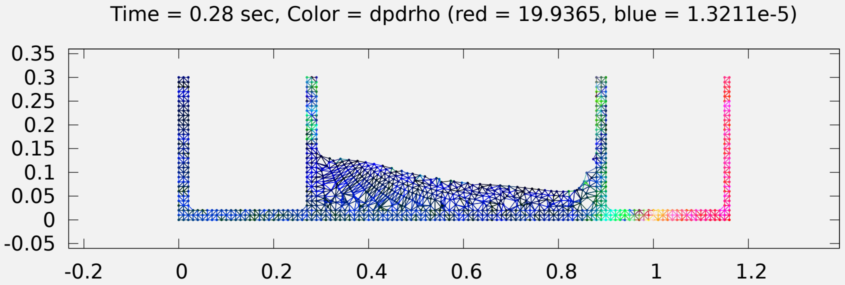
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution

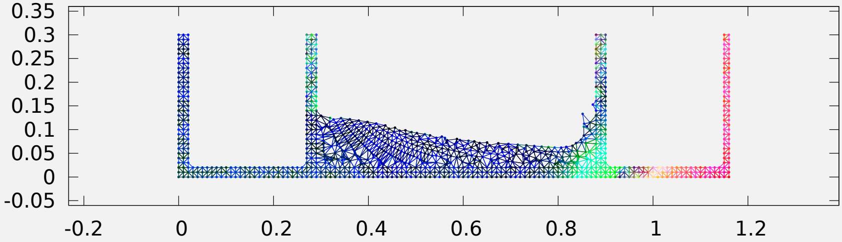


Water column collapse : pressure sensitivity distribution

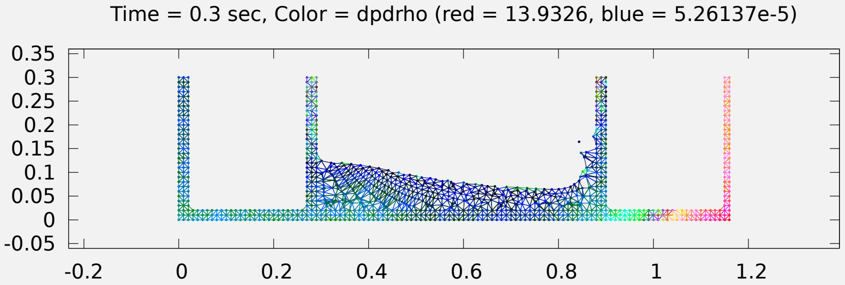


Water column collapse : pressure sensitivity distribution

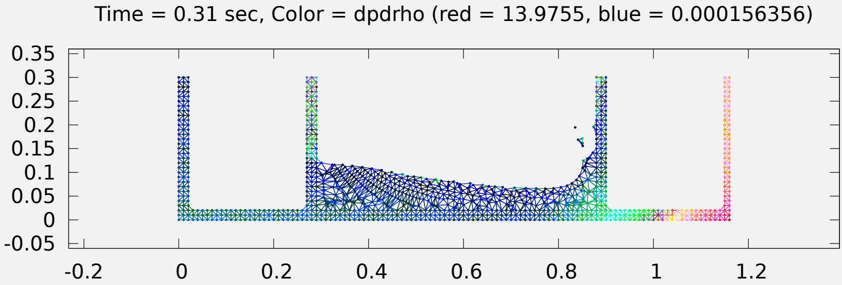
Time = 0.29 sec, Color = dpdrho (red = 22.4636, blue = 1.62874e-5)



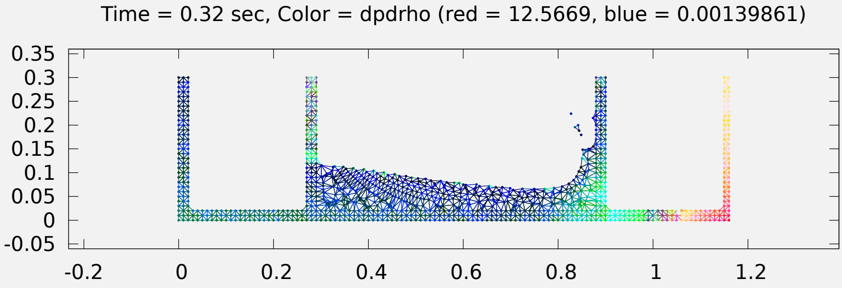
Water column collapse : pressure sensitivity distribution



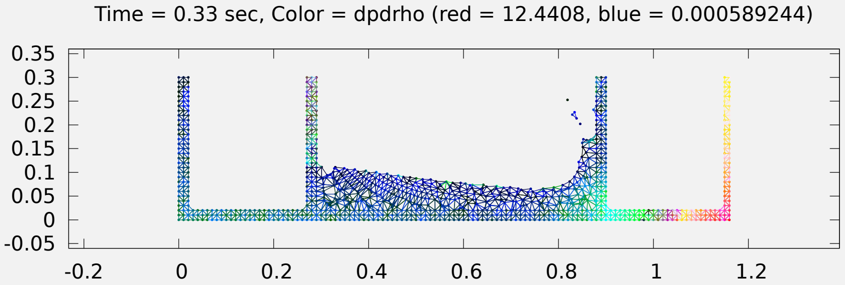
Water column collapse : pressure sensitivity distribution



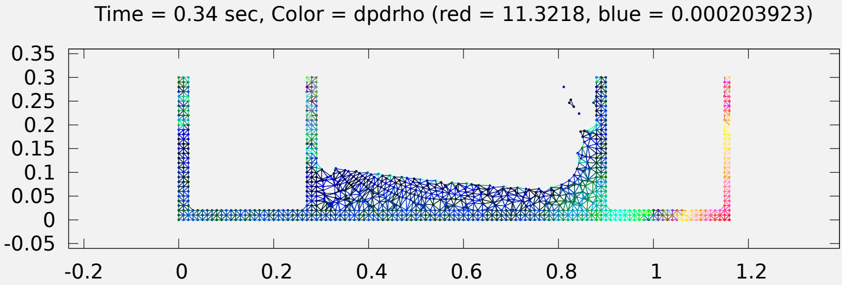
Water column collapse : pressure sensitivity distribution



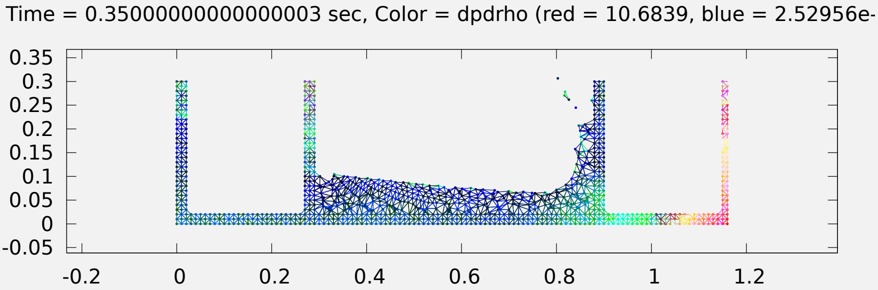
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution

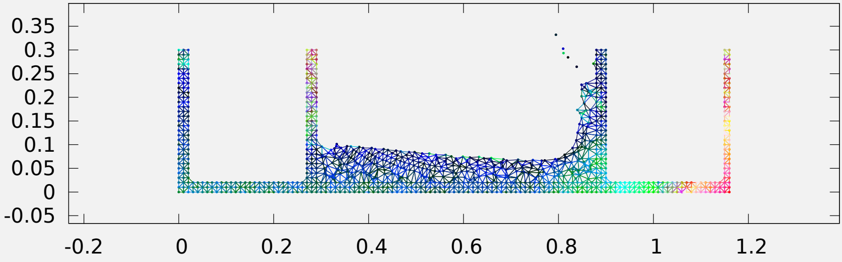


Water column collapse : pressure sensitivity distribution

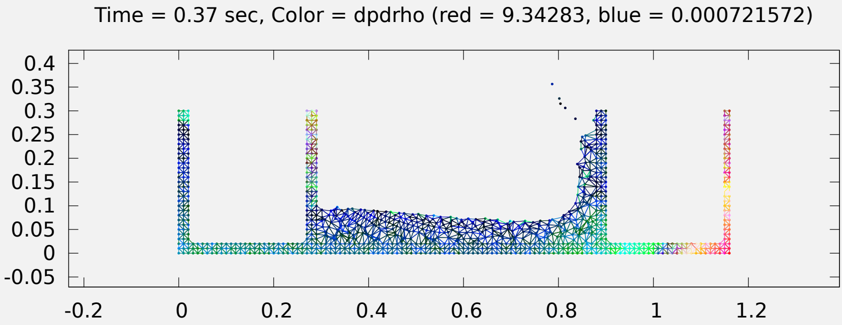


Water column collapse : pressure sensitivity distribution

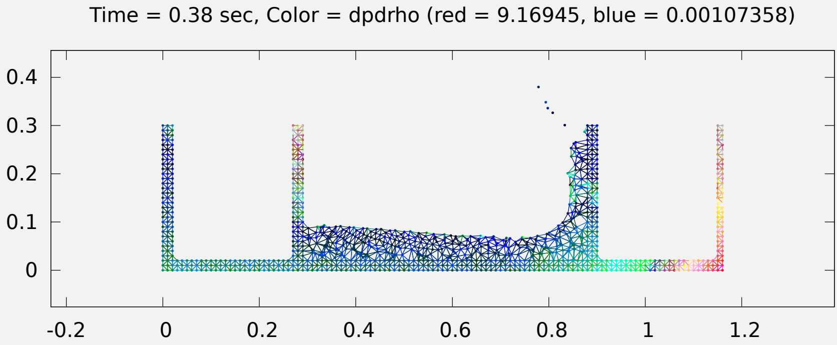
Time = 0.36 sec, Color = dpdrho (red = 9.76745, blue = 7.54104e-5)



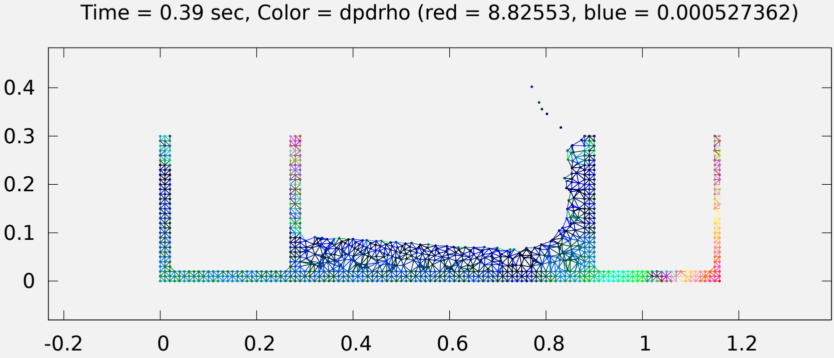
Water column collapse : pressure sensitivity distribution



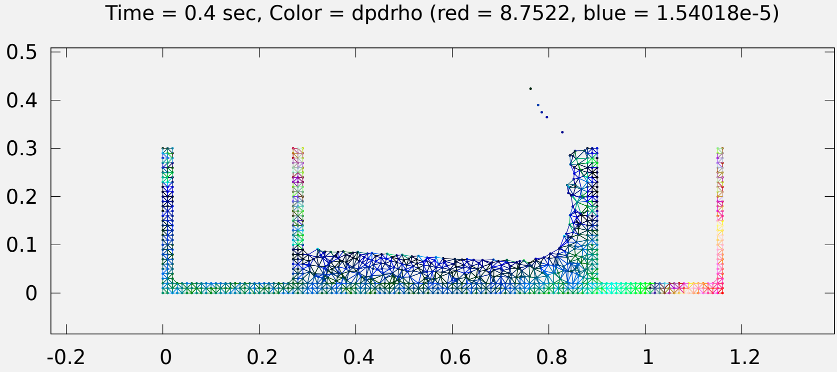
Water column collapse : pressure sensitivity distribution



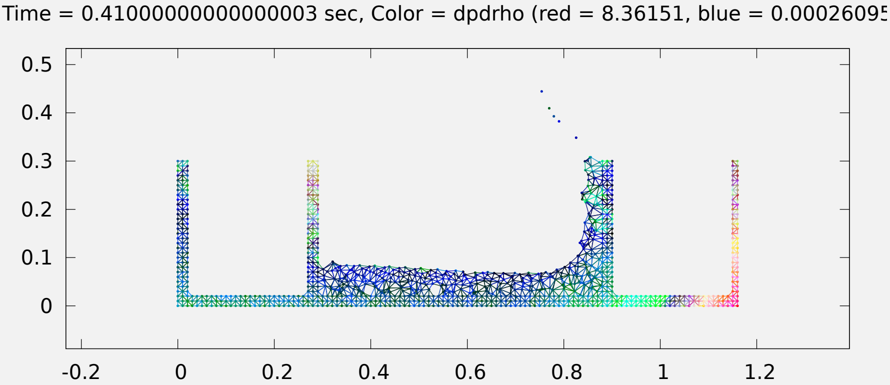
Water column collapse : pressure sensitivity distribution



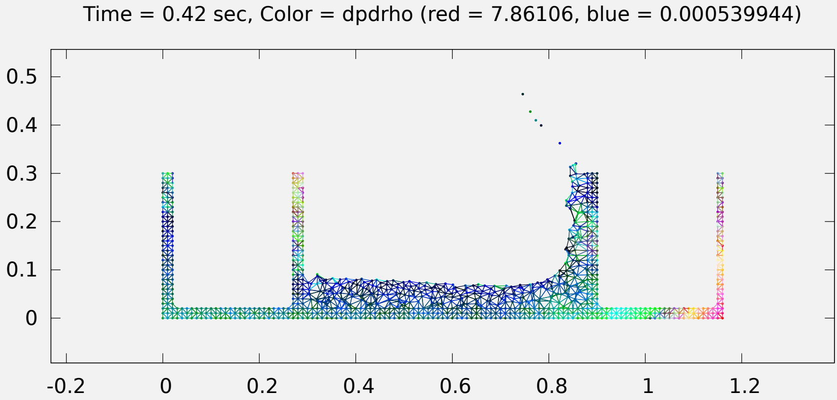
Water column collapse : pressure sensitivity distribution



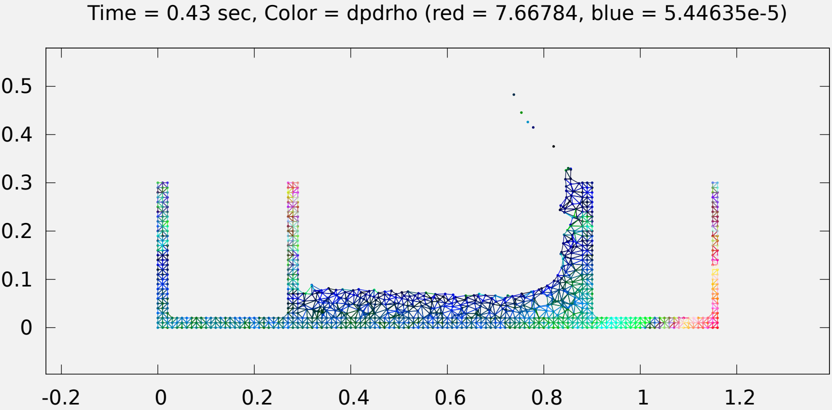
Water column collapse : pressure sensitivity distribution



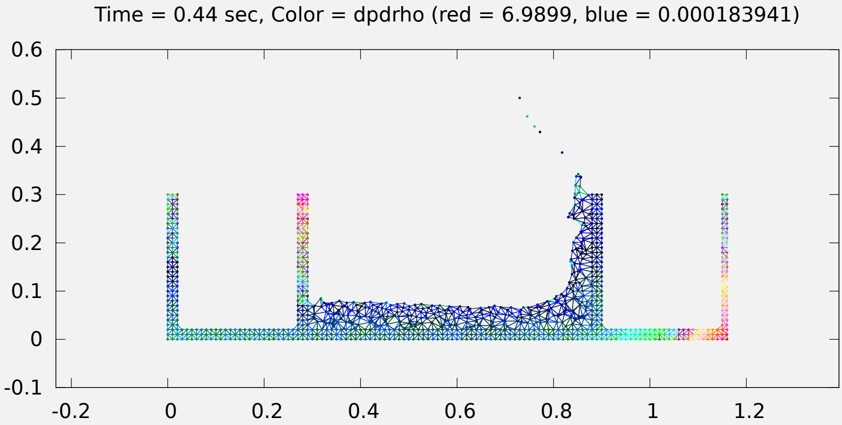
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution

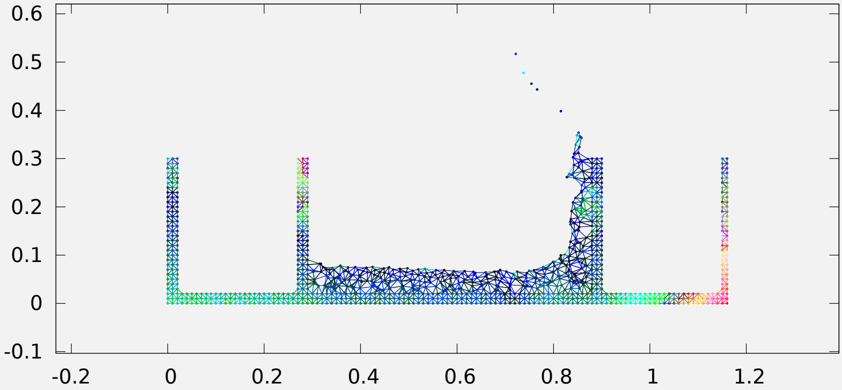


Water column collapse : pressure sensitivity distribution

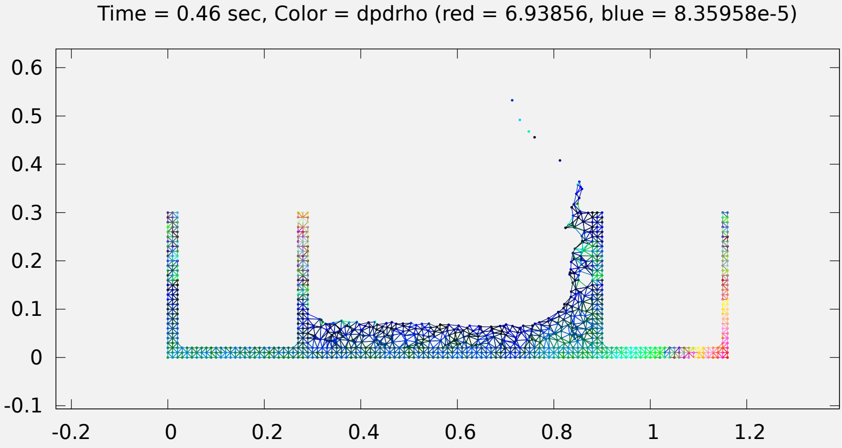


Water column collapse : pressure sensitivity distribution

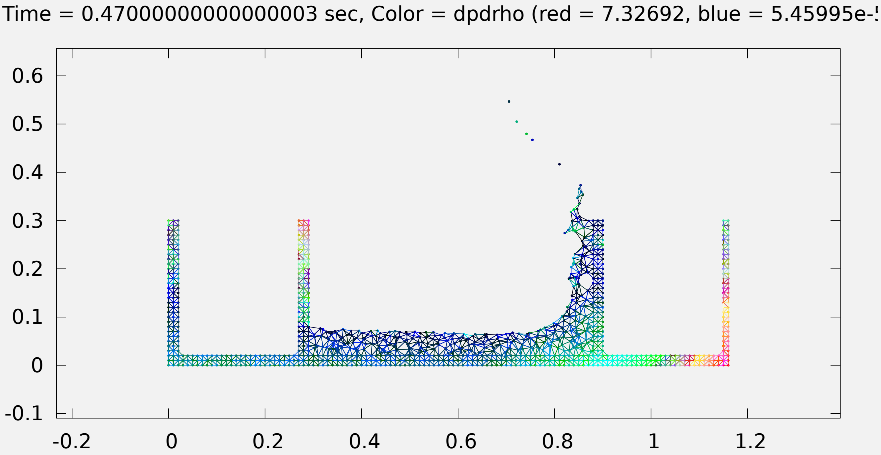
Time = 0.45 sec, Color = dpdrho (red = 6.6227, blue = 4.4567e-5)



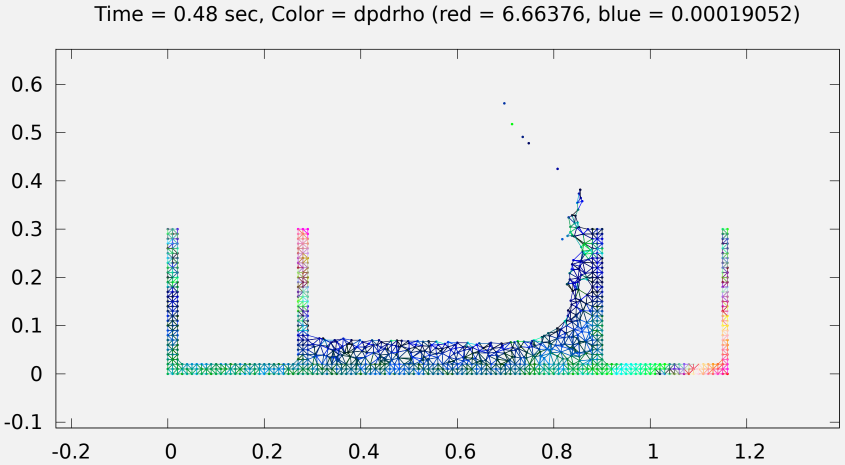
Water column collapse : pressure sensitivity distribution



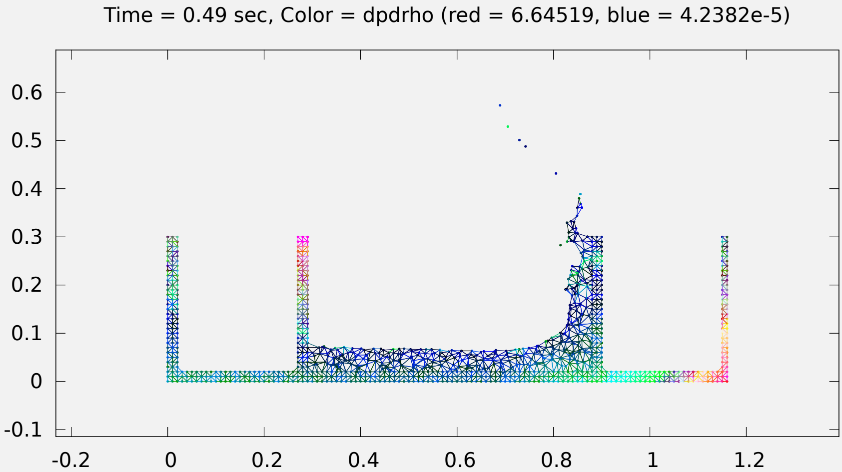
Water column collapse : pressure sensitivity distribution



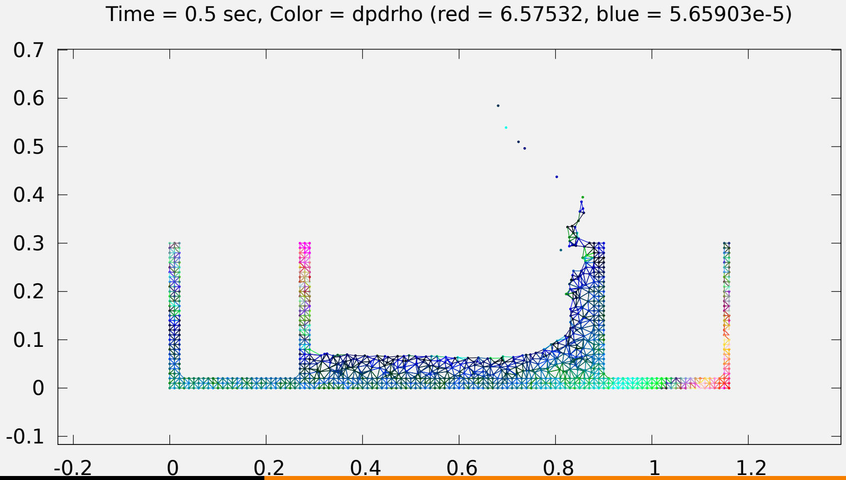
Water column collapse : pressure sensitivity distribution



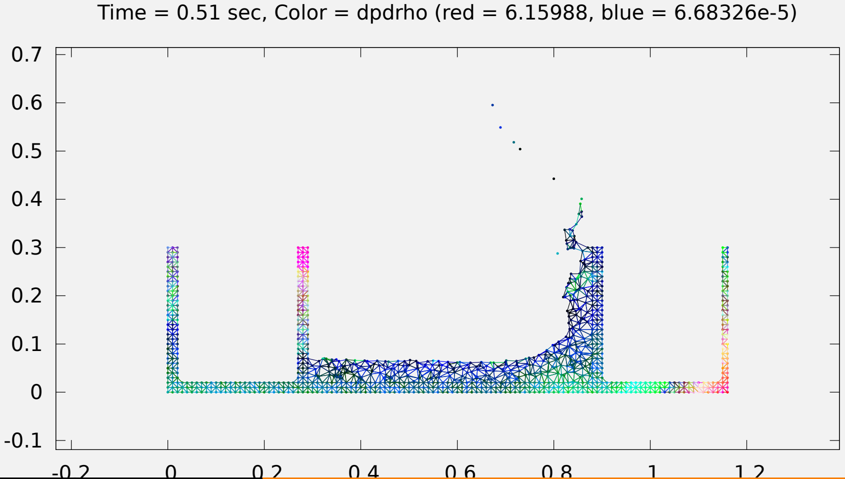
Water column collapse : pressure sensitivity distribution



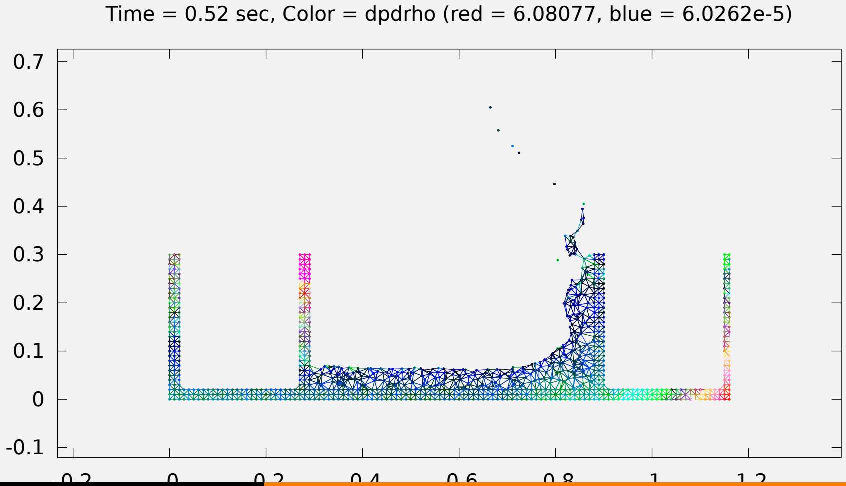
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution

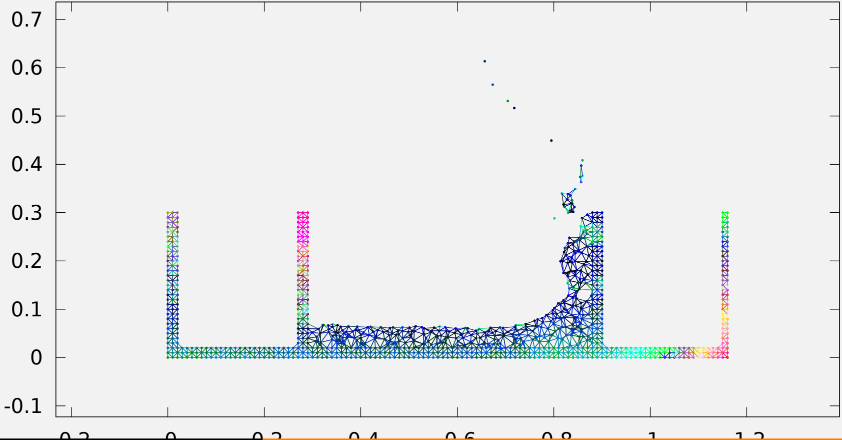


Water column collapse : pressure sensitivity distribution

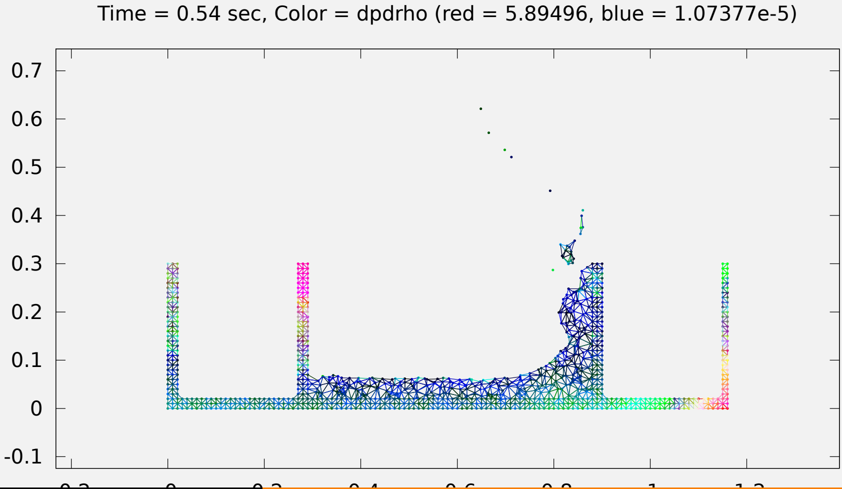


Water column collapse : pressure sensitivity distribution

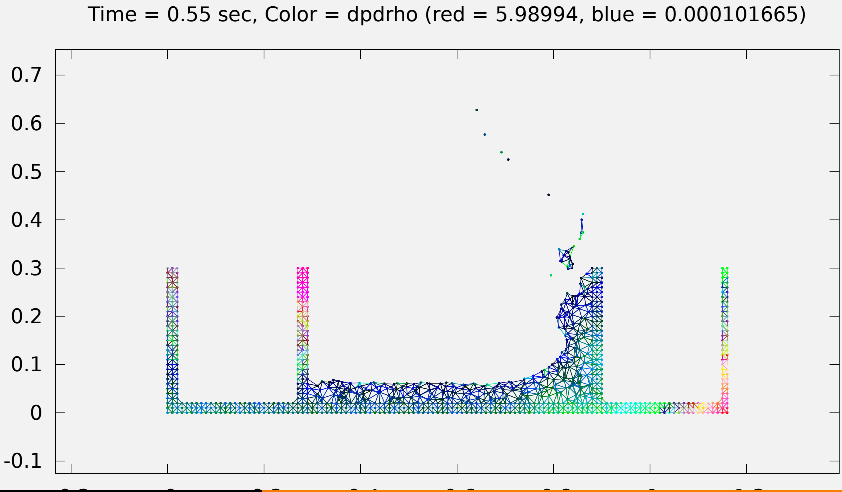
Time = 0.53 sec, Color = dpdrho (red = 5.95879, blue = 7.33743e-5)



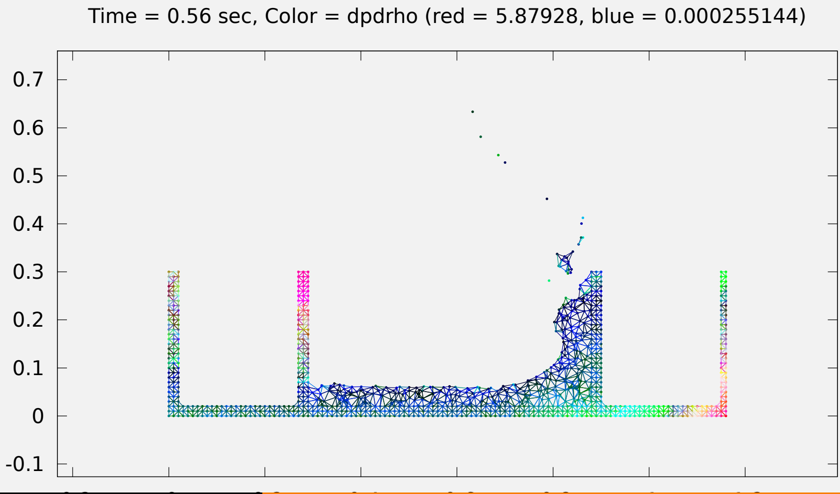
Water column collapse : pressure sensitivity distribution



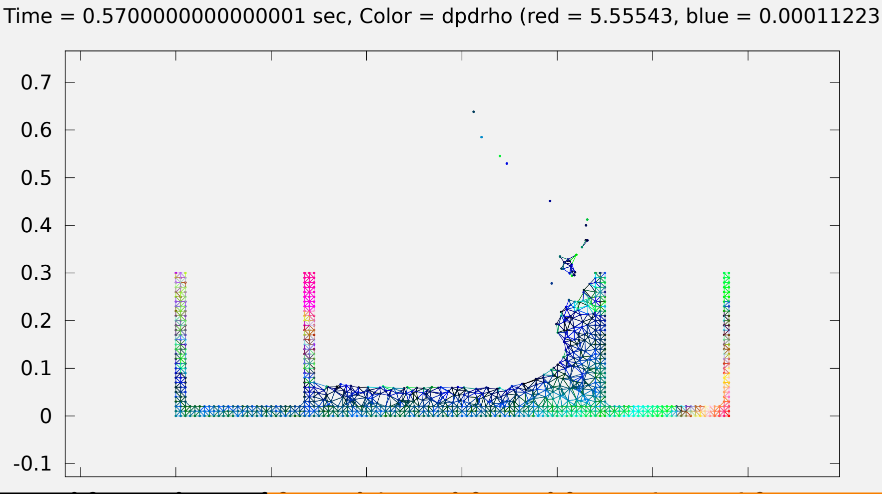
Water column collapse : pressure sensitivity distribution



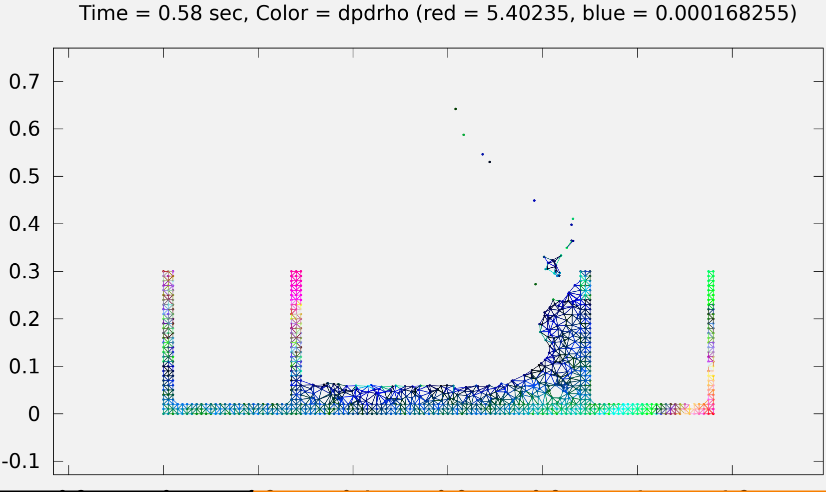
Water column collapse : pressure sensitivity distribution



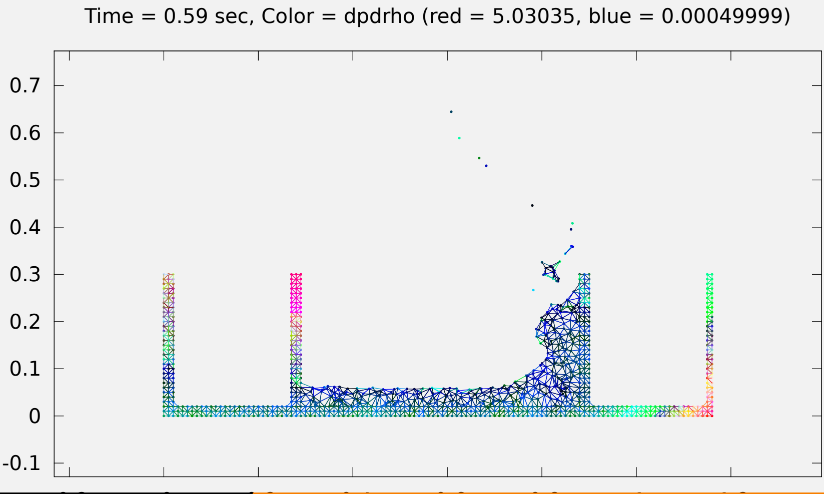
Water column collapse : pressure sensitivity distribution



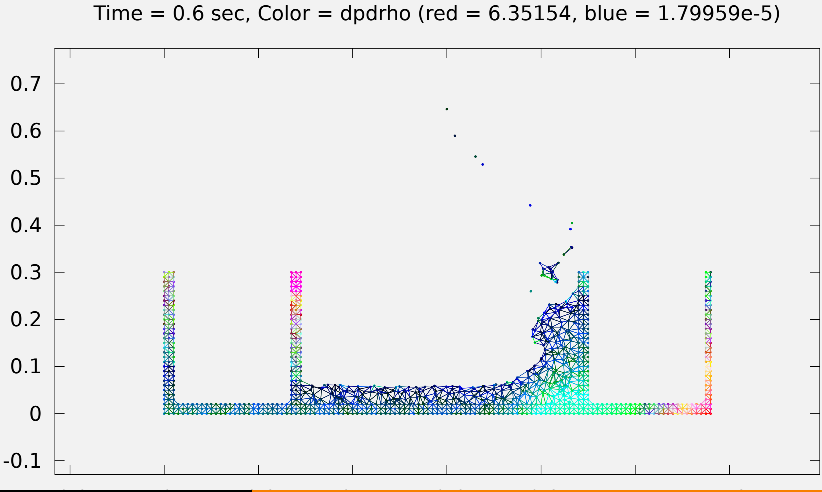
Water column collapse : pressure sensitivity distribution



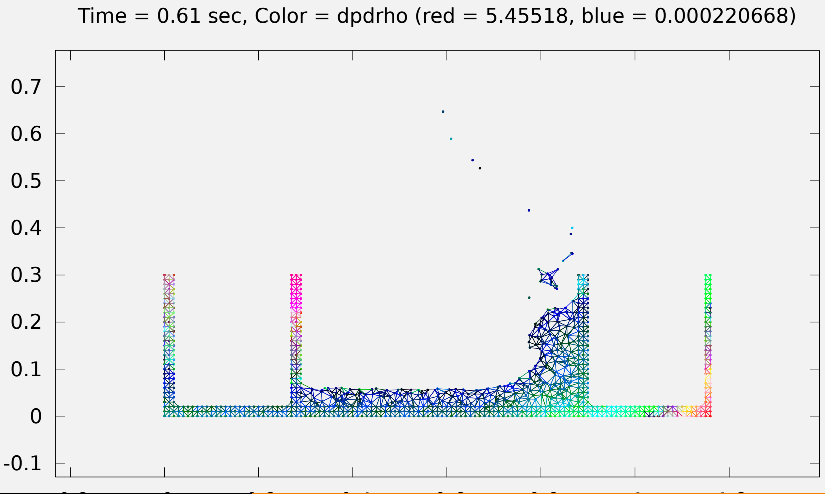
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution

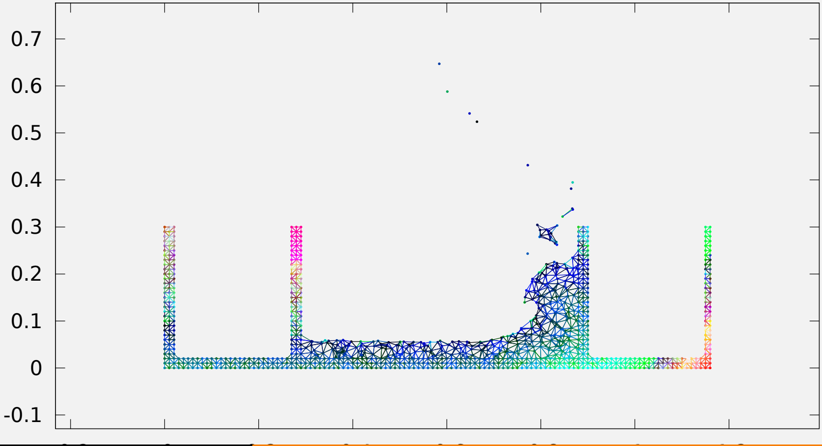


Water column collapse : pressure sensitivity distribution

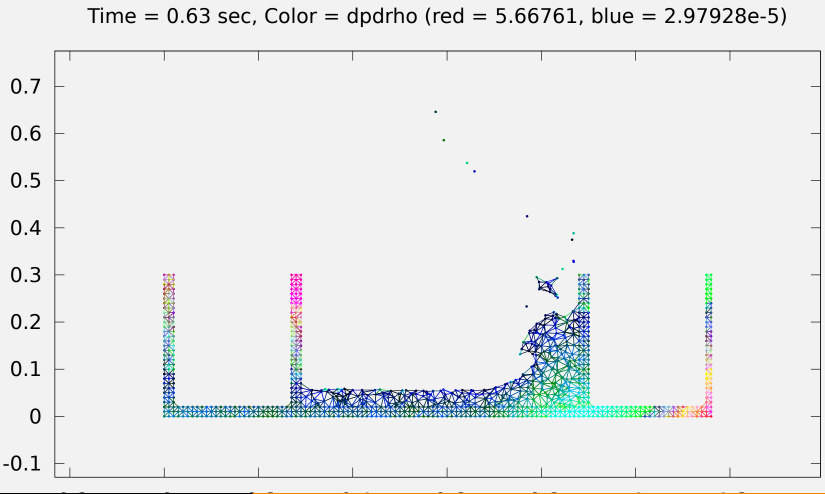


Water column collapse : pressure sensitivity distribution

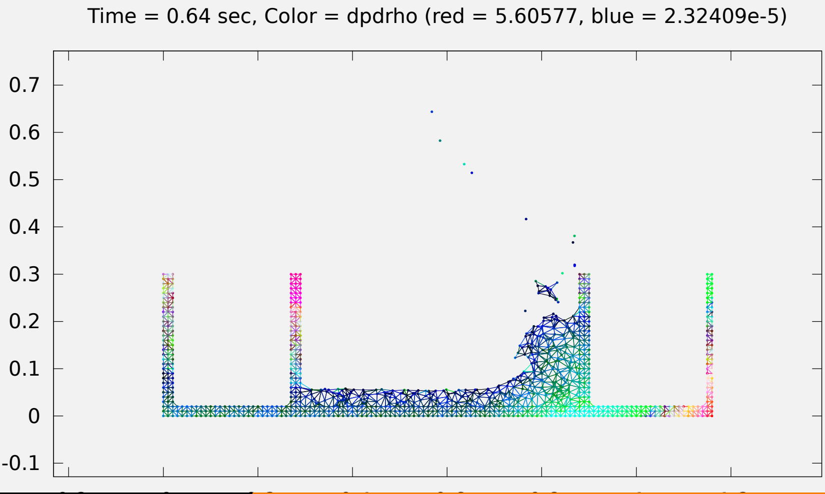
Time = 0.62 sec, Color = dpdrho (red = 5.43307, blue = 0.000260069)



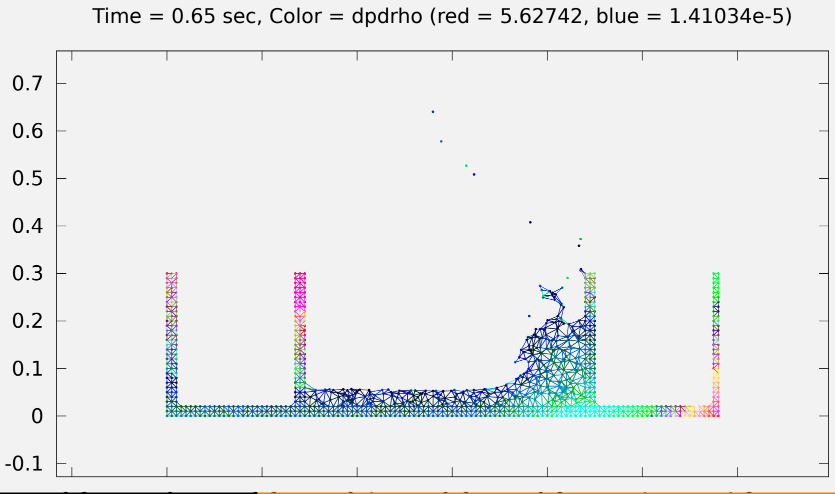
Water column collapse : pressure sensitivity distribution



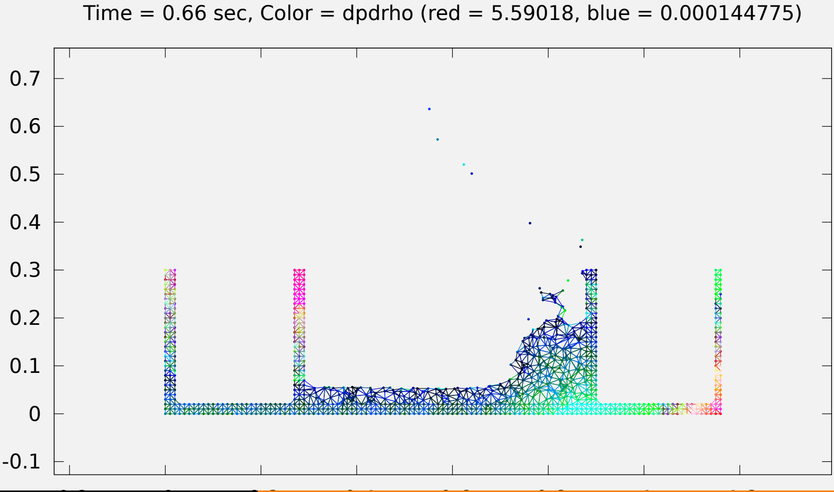
Water column collapse : pressure sensitivity distribution



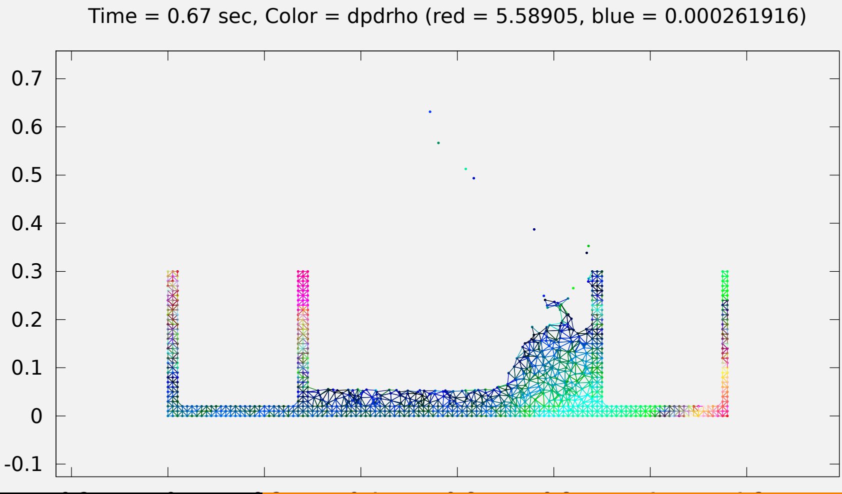
Water column collapse : pressure sensitivity distribution



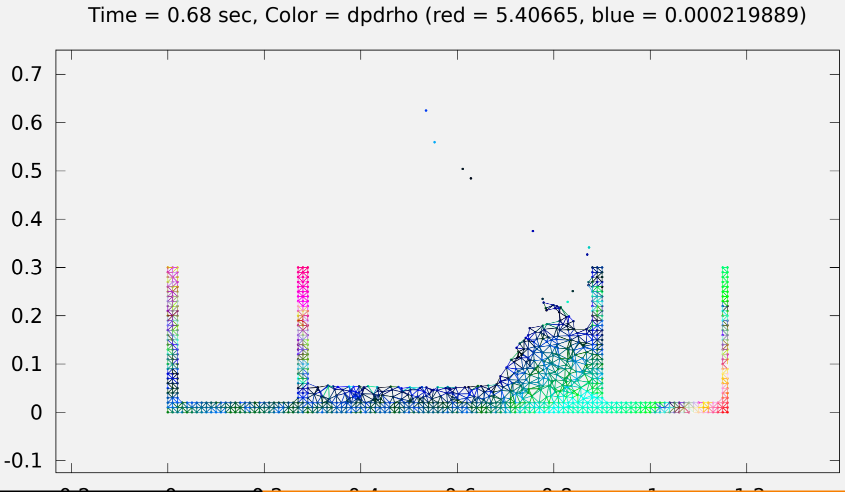
Water column collapse : pressure sensitivity distribution



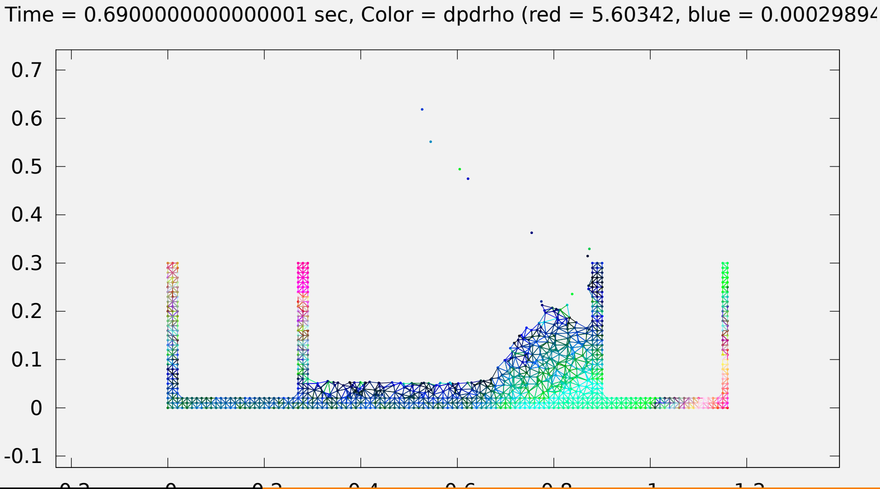
Water column collapse : pressure sensitivity distribution



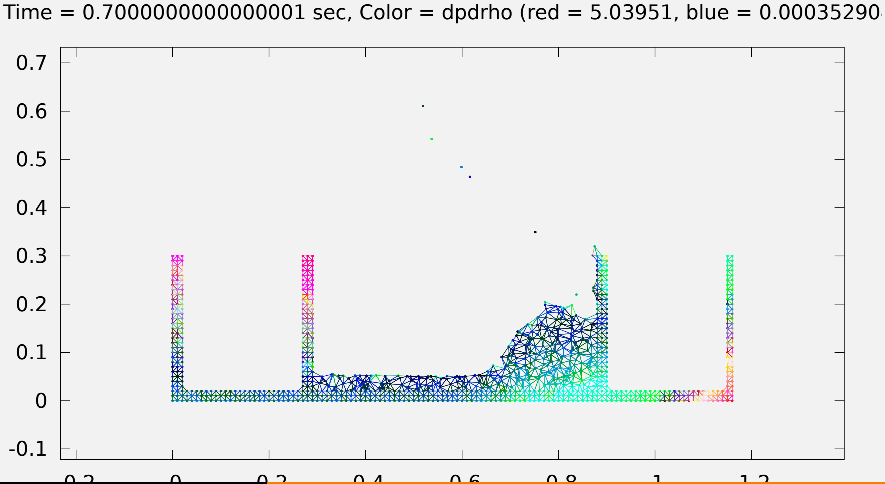
Water column collapse : pressure sensitivity distribution



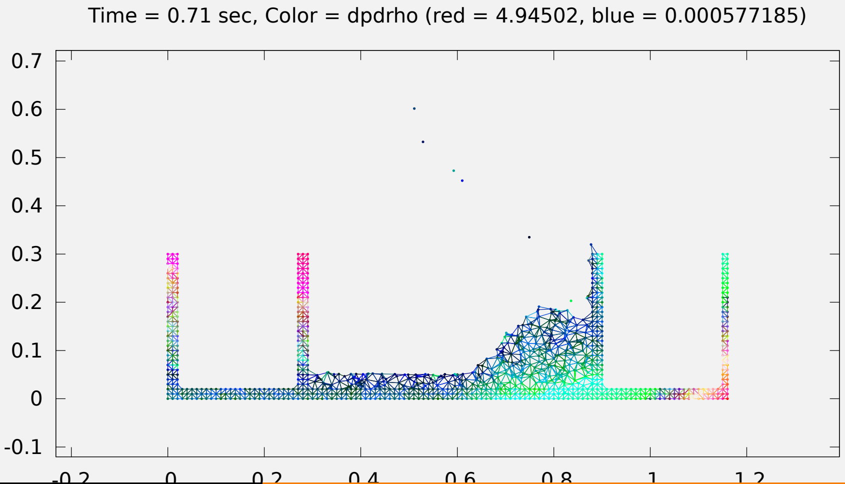
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution



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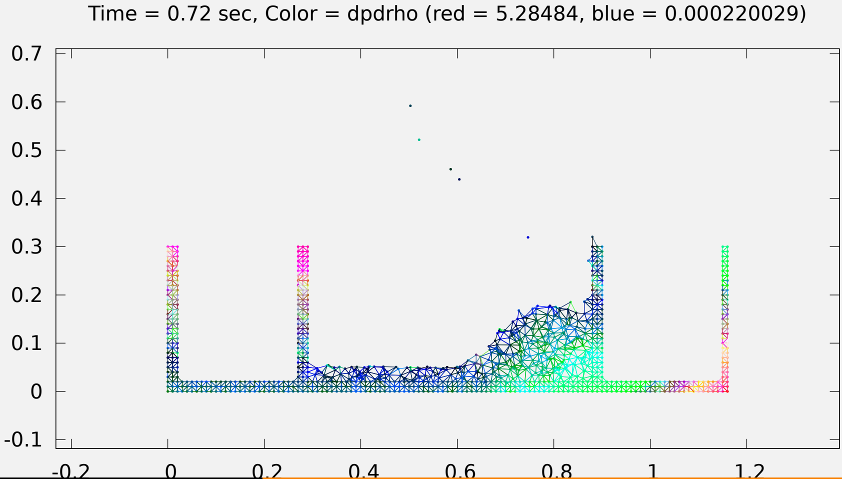

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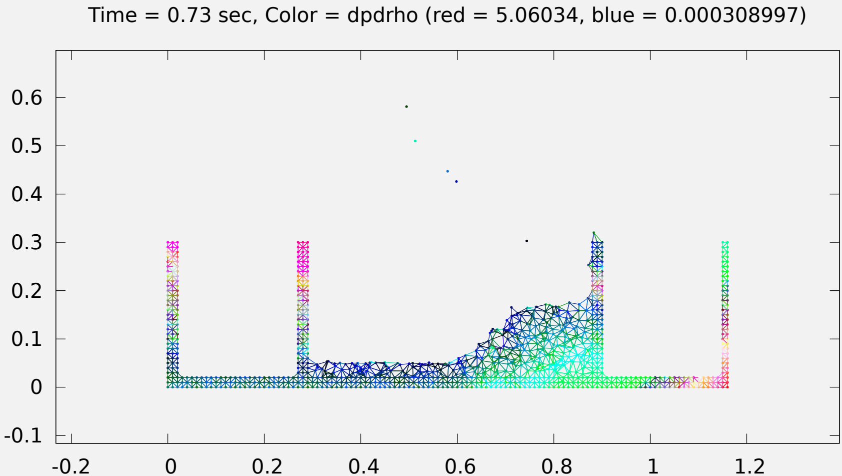

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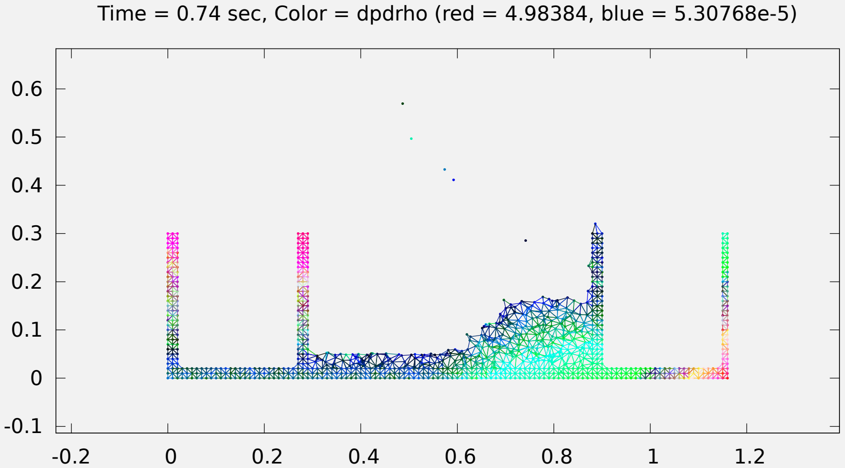
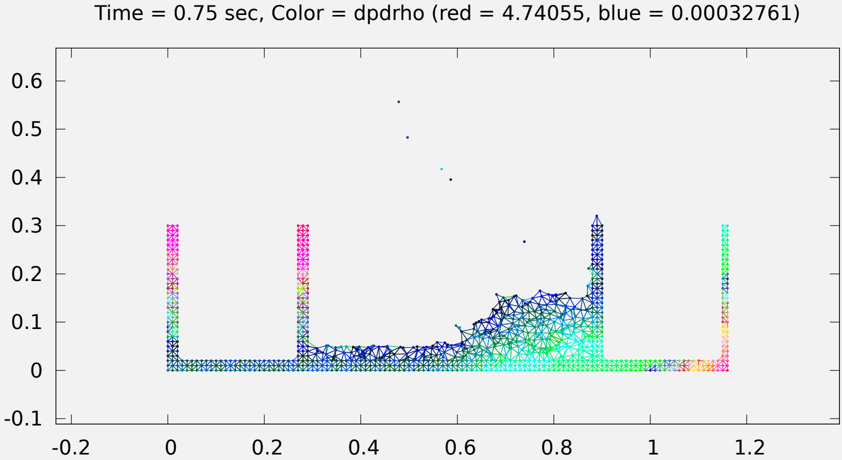
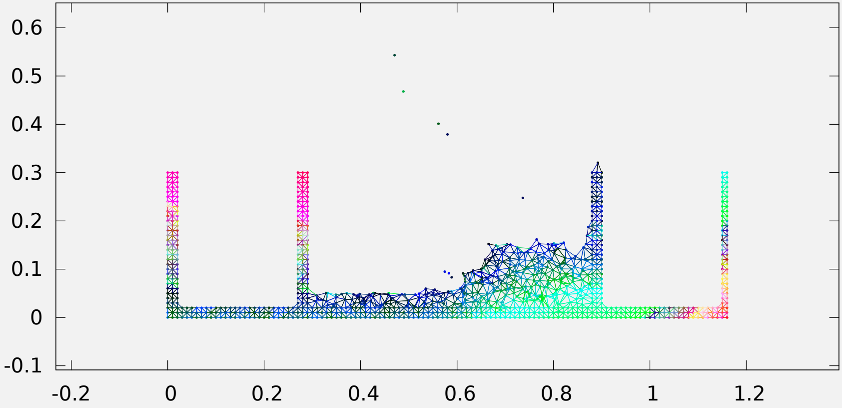


Water column collapse : pressure sensitivity distribution

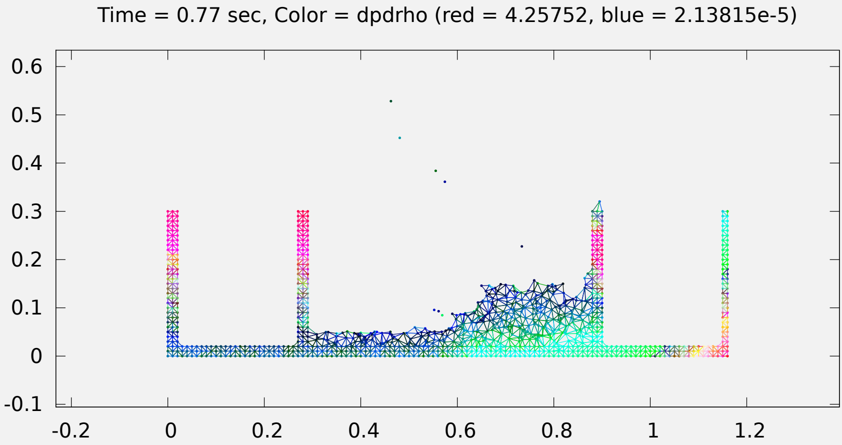


Water column collapse : pressure sensitivity distribution

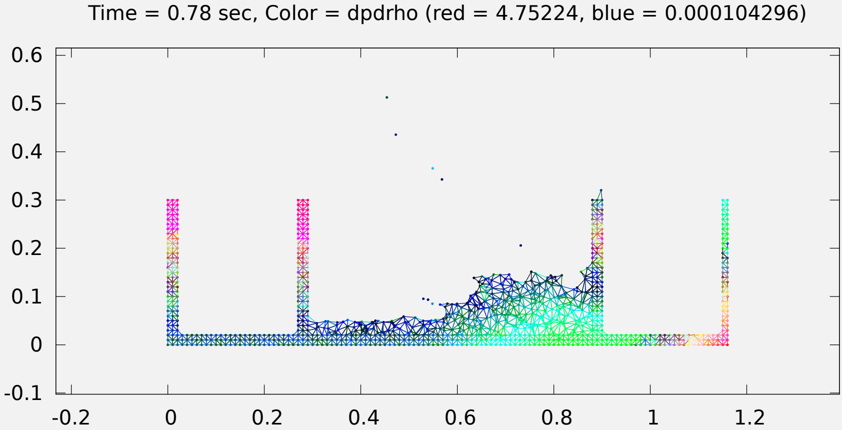
Time = 0.76 sec, Color = dpdrho (red = 4.59307, blue = 0.00188903)



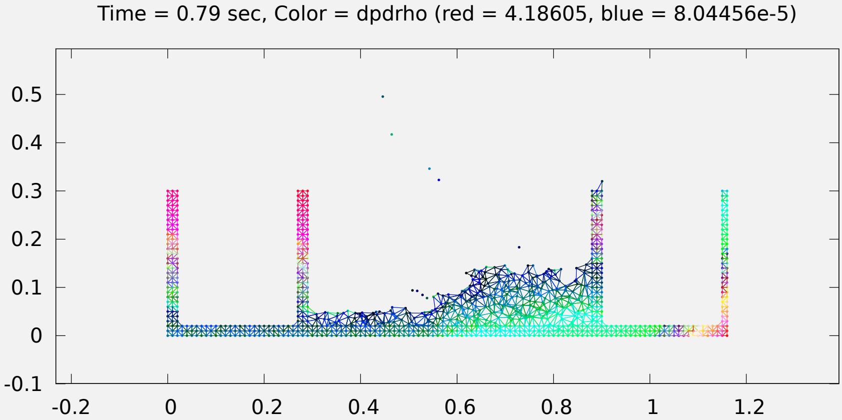
Water column collapse : pressure sensitivity distribution



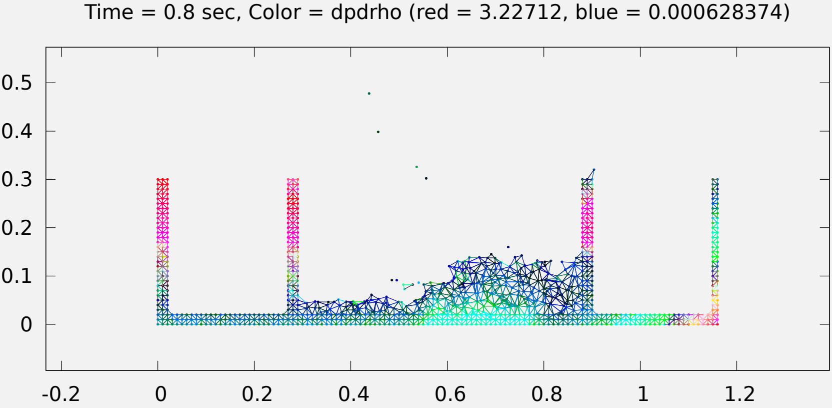
Water column collapse : pressure sensitivity distribution



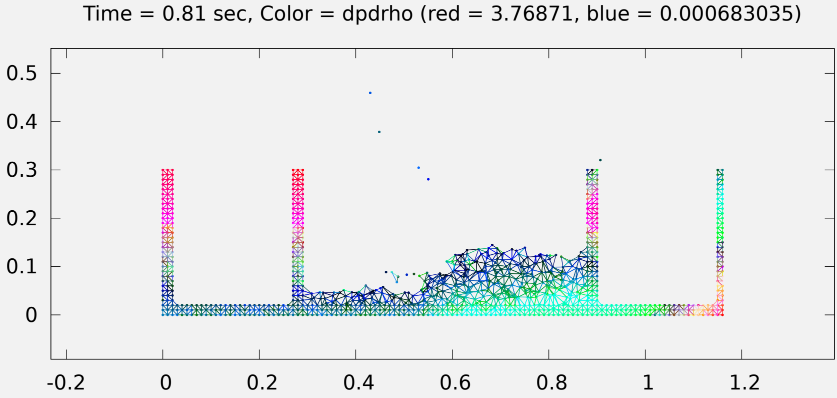
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution



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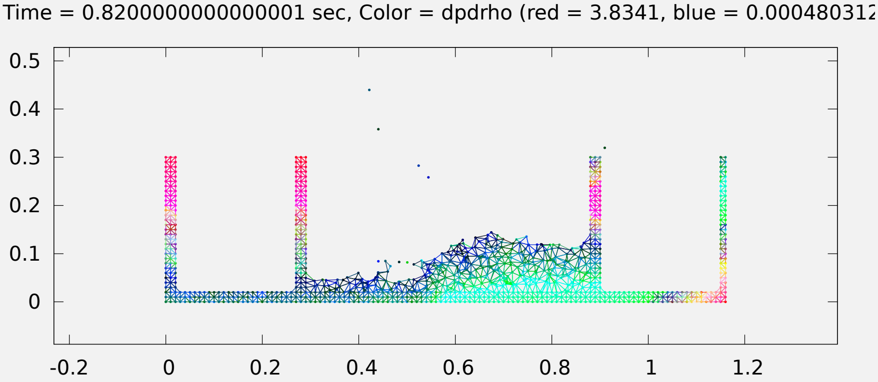
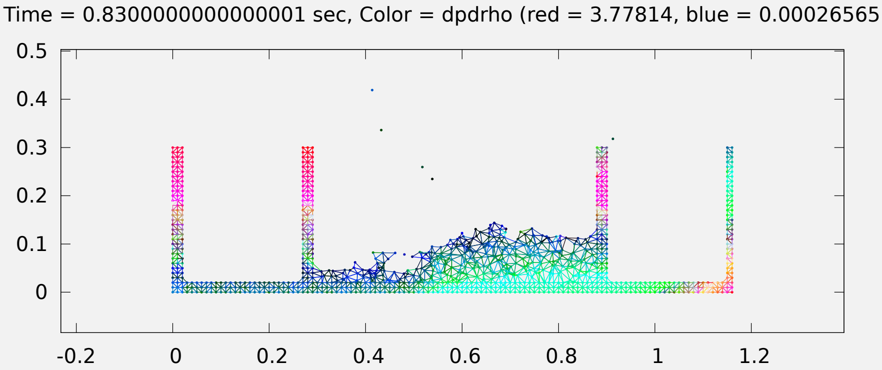
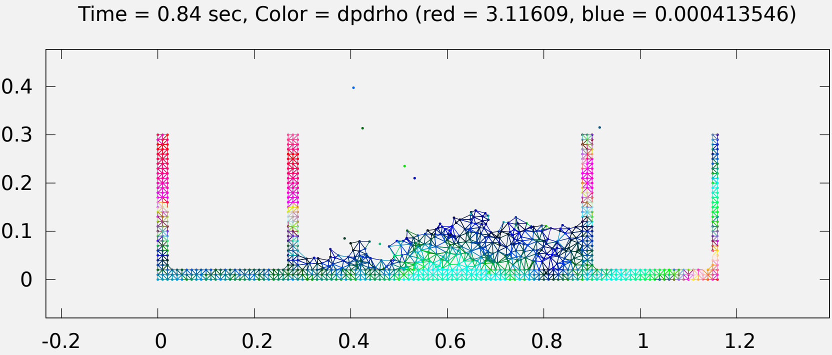


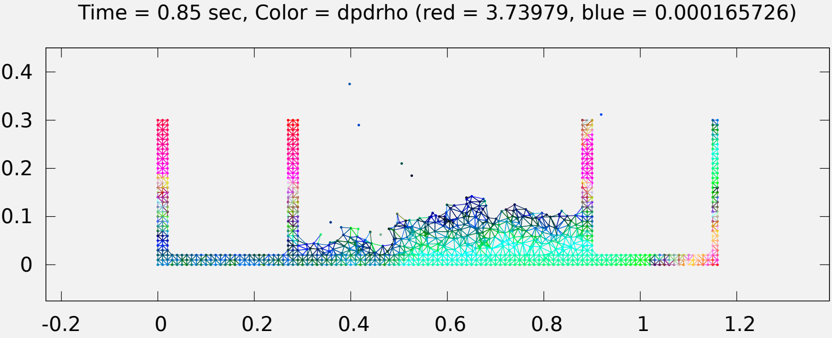
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution



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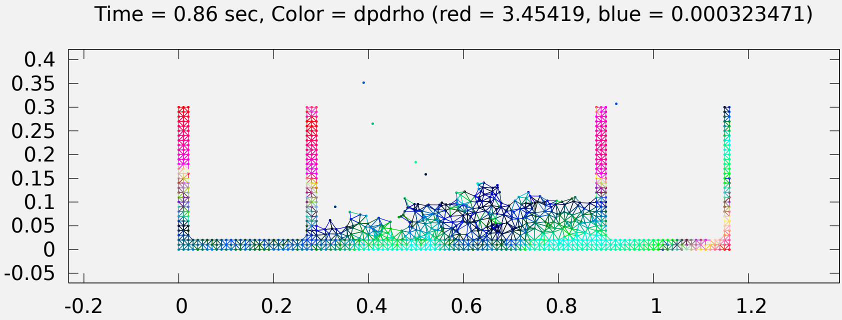

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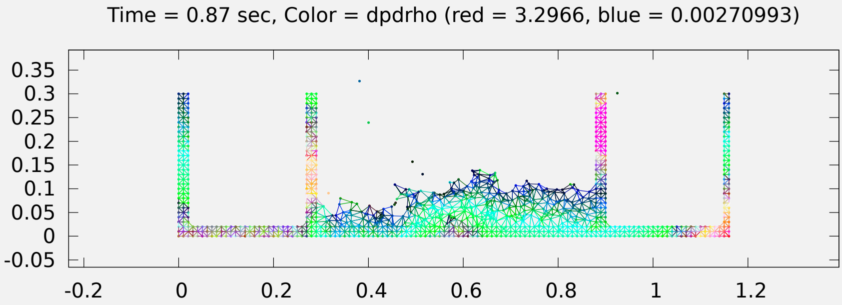

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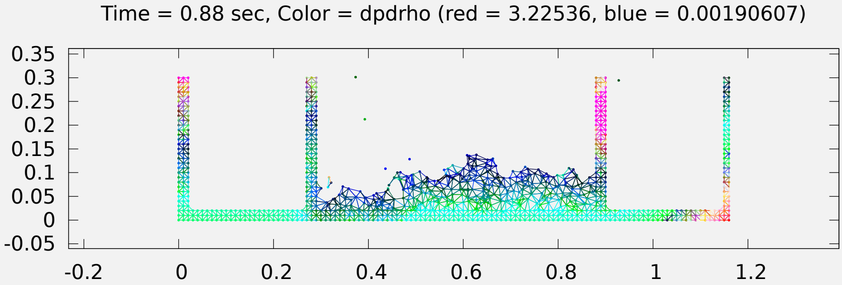
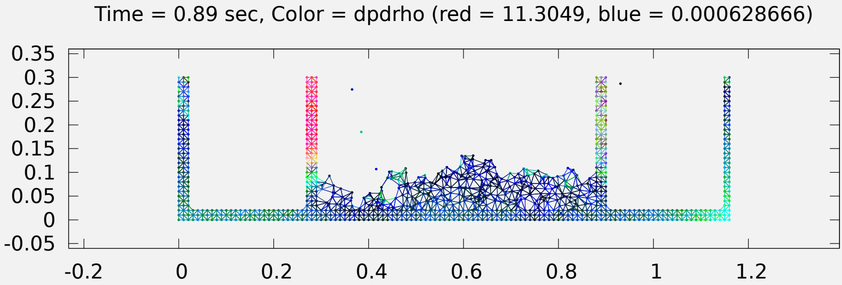
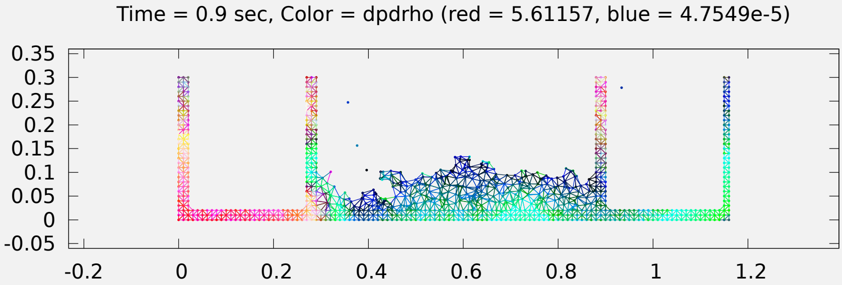


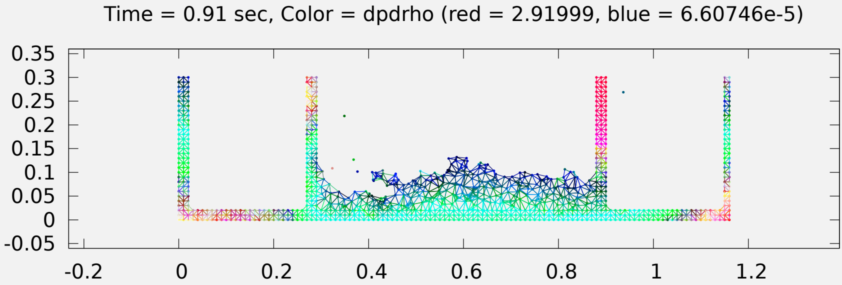
Water column collapse : pressure sensitivity distribution



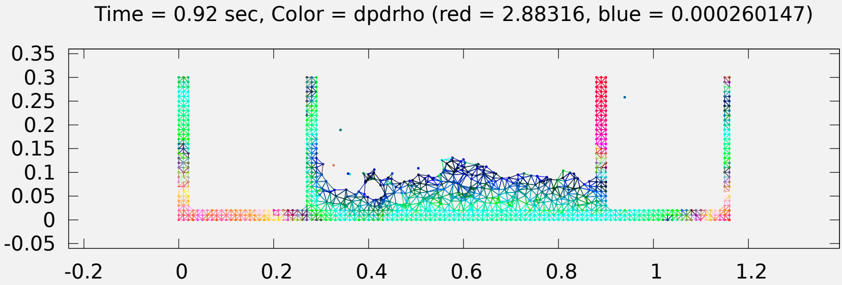
Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution



Water column collapse : pressure sensitivity distribution



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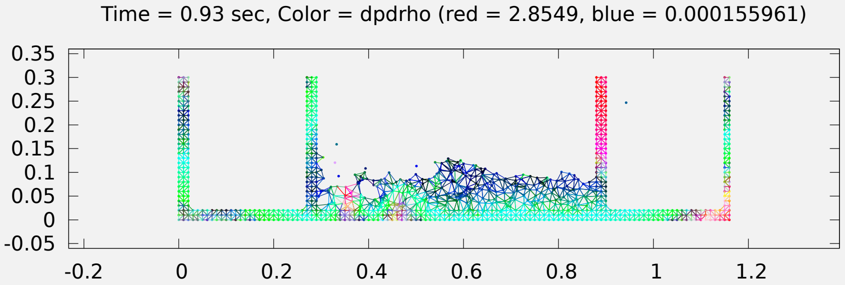

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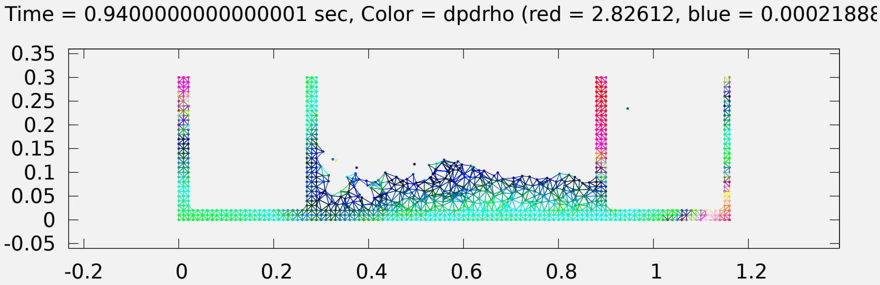

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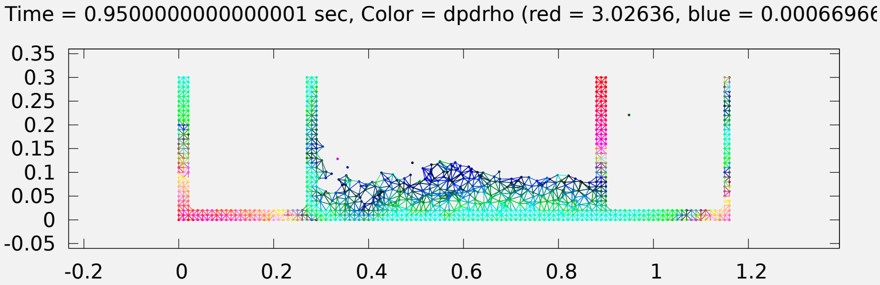

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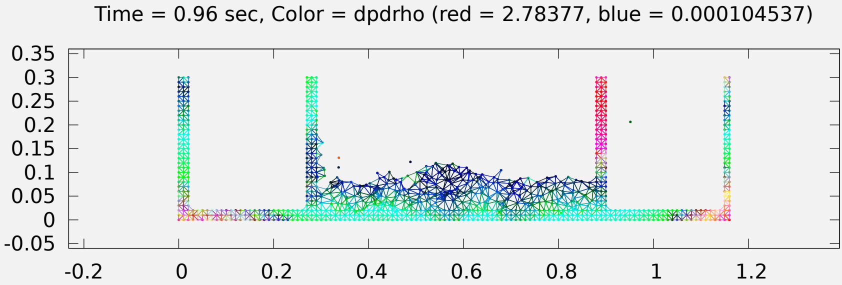

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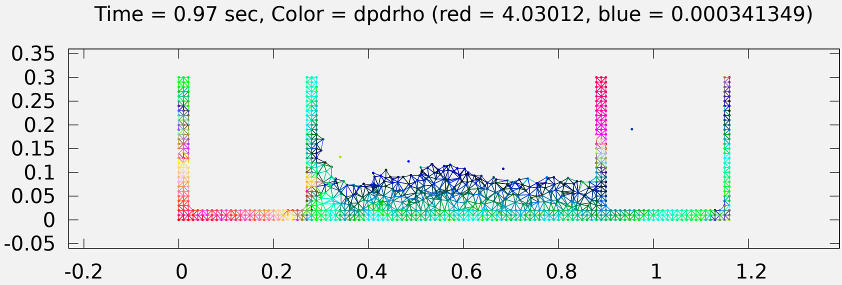
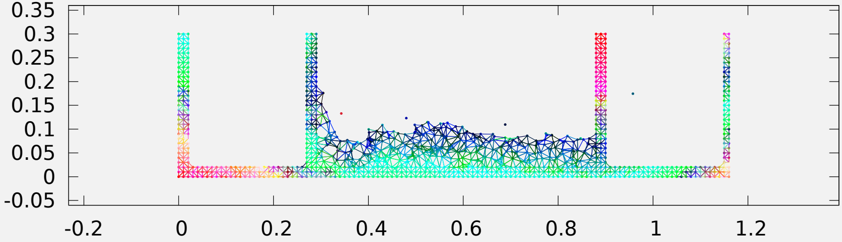
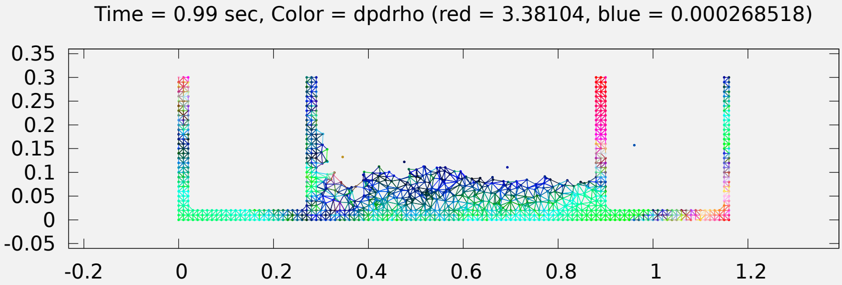


Water column collapse : pressure sensitivity distribution

Time = 0.98 sec, Color = dpdrho (red = 2.9524, blue = 4.2978e-5)



Water column collapse : pressure sensitivity distribution



Conclusions and future work

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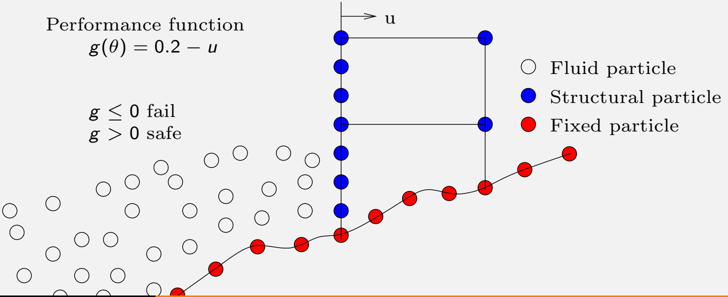

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WHERE DISCOVERIES BEGIN

Questions?