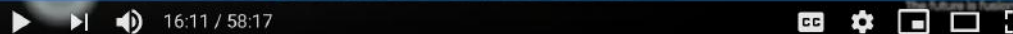


Incompressible Navier-Stokes equations

- The Navier-Stokes equations are sensitive to scale, so we simulate them at 0.004x scale relative to the physical environment.

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Smoothed Particle Hydrodynamics

- [Monaghan 1992] introduced smoothing kernels W

$$A_i(r) = \int A(r') W(r-r', h) dr' \approx \sum_b A(r_b) W(r-r_b, h)$$

- And approximations to terms of the N-S equations
- $\rho_i \approx \sum_j m_j W(r-r_j, h)$ m - mass, r - position, h - radius

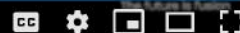
$$\frac{\nabla p_i}{\rho_i} \approx \sum_j m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} \right) \nabla W(r-r_j, h)$$

$$\frac{\mu}{\rho_i} \nabla^2 v_i \approx \frac{\mu}{\rho_i} \sum_j m_j \left(\frac{v_j - v_i}{\rho_j} \right) \nabla^2 W(r-r_j, h)$$

12.1 Smoothed Particle Hydrodynamics | November 2010



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Smoothed Particle Hydrodynamics

- From Navier-Stokes to SPH:

$$\frac{dv_i}{dt} = g - \frac{1}{\rho_i} \nabla p + \frac{\mu}{\rho_i} \nabla^2 v \quad (1)$$

$$\rho_i \approx \sum_j m_j \frac{315}{64 \pi h^9} (h^2 - \|r - r_b\|^2)^3 \quad (2)$$

$$\frac{\nabla p_i}{\rho_i} \approx \sum_j m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} \right) \frac{-45}{\pi h^6} (h - \|r - r_b\|)^2 \frac{r - r_b}{\|r - r_b\|} \quad (3)$$

$$\frac{\mu}{\rho_i} \nabla^2 v_i \approx \frac{\mu}{\rho_i} \sum_j m_j \left(\frac{v_j - v_i}{\rho_j} \right) \frac{45}{\pi h^6} (h - \|r - r_b\|) \quad (4)$$

Video 1.4.1 Smoothed Particle Hydrodynamics | November 2010



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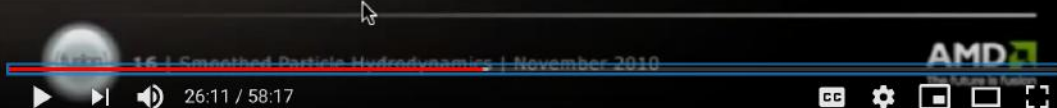
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OpenCL simulation

- Numerical algorithm:
 - density ρ = equation (2).
 - pressure $p = k(\rho - \rho_0)$
 - pressure gradient $\frac{\nabla p_i}{\rho_i}$ = equation (3).
 - viscous term $\frac{\mu}{\rho_i} \nabla^2 v_i$ = equation (4).
 - acceleration = equation (1).
 - numerically integrate velocity, position.



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OpenCL simulation

- A naïve algorithm computes interactions among all particles
 - Gives correct result because $W = 0$ for particles beyond the interaction radius
 - But this has complexity $O(n^2)$
 - Need an algorithm that only computes interactions among particles that are within the interaction radius

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OpenCL simulation

- A better algorithm partitions space into local regions
 - Divide into voxels of size $2h$ on a side
 - Each particle can only interact with particles in the same voxel, and in immediately adjacent voxels
 - Total search volume = $2 \times 2 \times 2$ voxels
 - Further refinement: compute interactions with a limited number m of particles
 - $m = 32$ works well

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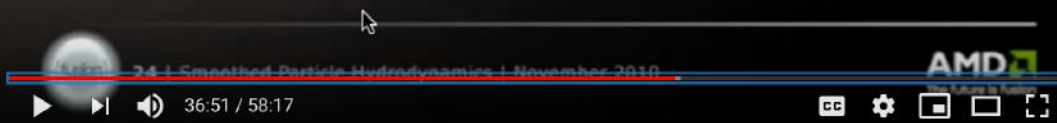
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OpenCL simulation

- The final algorithm:
 - Organize particles into voxels
 - hashParticles, sort, sortPostPass
 - Compute spatial index from voxel to particles
 - indexx, indexPostPass
 - For every particle
 - Examine local region of 2x2x2 voxels
 - findNeighbors
 - Compute interactions with 32 particles
 - computeDensityPressure, computeAcceleration, integrate



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OpenCL simulation

- Organize particles into voxels: `global_id(0)=particle id`
 - hashParticles:
 - computes a scalar voxel id from position
 - Voxel size $2h \times 2h$
 - stores voxel id in `position.w`;
 - writes `{voxel id, global_id(0)}` to `particleIndex`
 - sort:
 - sorts `particleIndex` by voxel id
 - radixSort works only on GPU, use qsort on CPU
 - sortPostPass:
 - rewrite `position, velocity` into `sortedPosition, sortedVelocity` according to order of `particleIndex`



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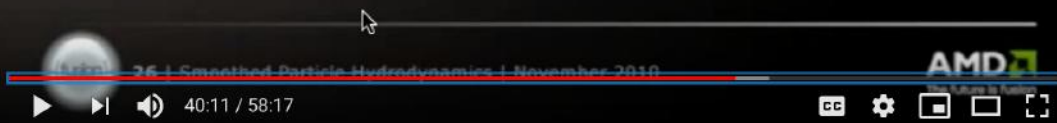
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OpenCL simulation

- Compute spatial index from voxel to particles:
global_id(0) = voxel id
 - indexx:
 - computes gridCellIndex(i), index into sortedPosition of first particle in voxel i
 - Binary search in sortedPosition for lowest particle id
 - Leave -1 for empty voxels
 - indexPostPass:
 - Fills in index for empty voxels
 - gridCellIndex(i) = gridCellIndex(i+1) for i empty, i+1 nonempty



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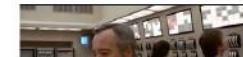
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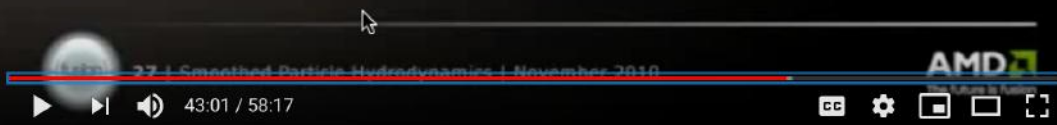
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OpenCL simulation

- Examine local region of $2 \times 2 \times 2$ voxels:
 - findNeighbors:
 - Locates particle in one corner of $2 \times 2 \times 2$ voxel set
 - Searches up to 8 voxels until 32 neighbors are found
 - Retains only neighbors within interaction radius
 - Within each voxel search is randomized
 - Necessary to eliminate biasing artifacts
 - Specifically, compute random offset within voxel, then proceed sequentially
 - Alternate sequential directions according to odd/evenness of particle



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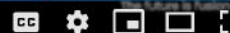
Summary

- Fluids
 - Governed by pressure, velocity
- Navier-Stokes equations
 - Incompressible equations, material derivative
- Smoothed Particle Hydrodynamics
 - Smoothing kernel approximations
 - Approximate ρ , ∇p , $\nabla^2 v$
- OpenCL simulation
 - Organize into voxels, create voxel index, compute equations (2), (3), (4), (1), integrate

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