Virtual Fluids – Real Insights

Computer Aided Product Development

Modeling, Simulation and Rendering in the Industry

Markus Ihmsen
www.fifty2.eu / ihmsen@fifty2.eu

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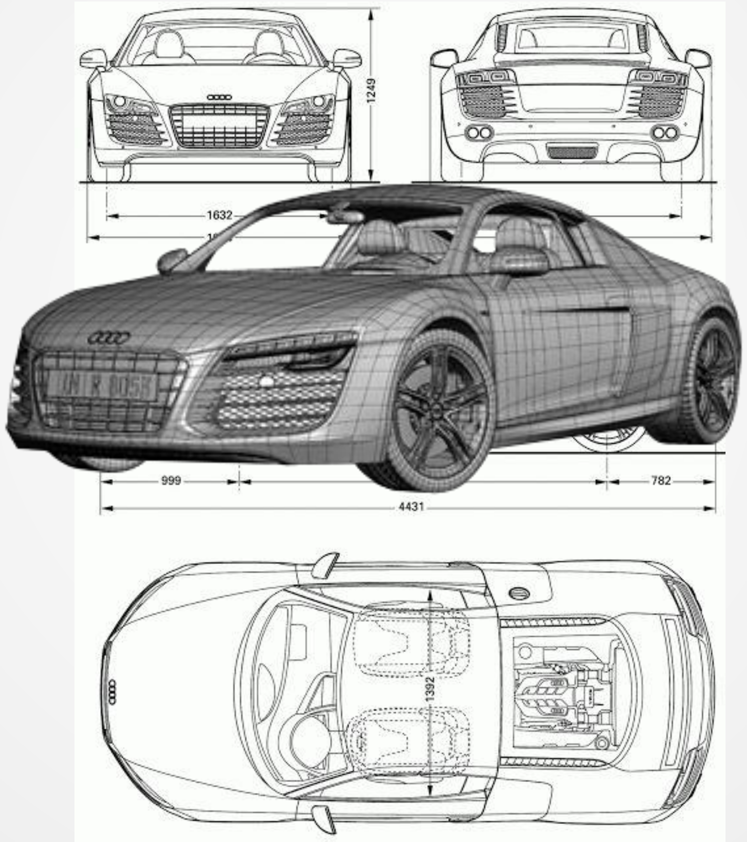
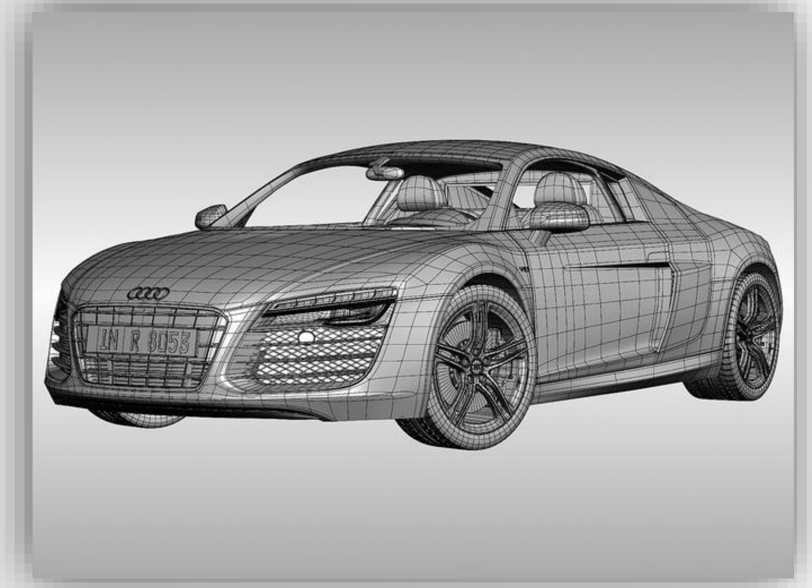
// Product development - an iterative process





1 – 2 Years

Question → Insights

// Problem

- Without simulation:
  - physical prototype required
  - complicated, expensive and unflexible tests

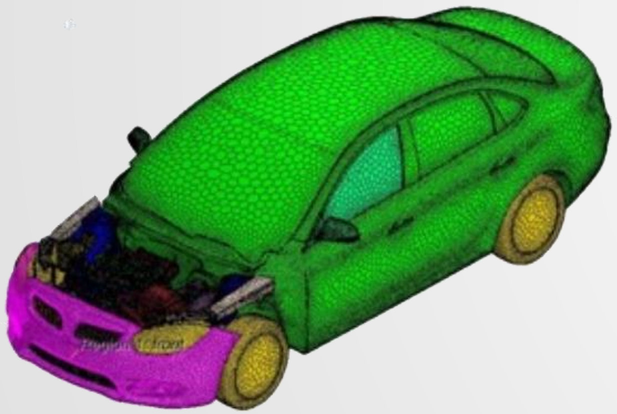
- Simulation tools:
  - require specialized knowledge by experts in the relevant simulation field
  - are slow

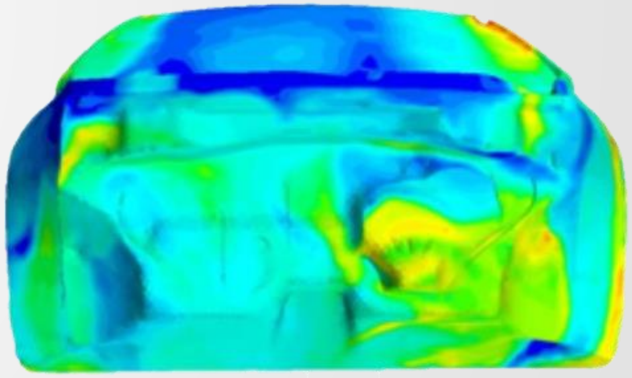
  -> complicated and time-consuming workflows

// Traditional simulation methods

Workflow wading simulation (grid-based):

3 weeks meshing (manual work) → 4 weeks simulation → 1 week data analysis





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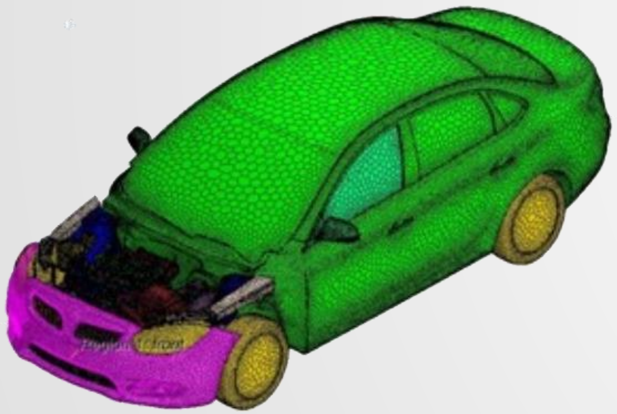


// Product development - an iterative process

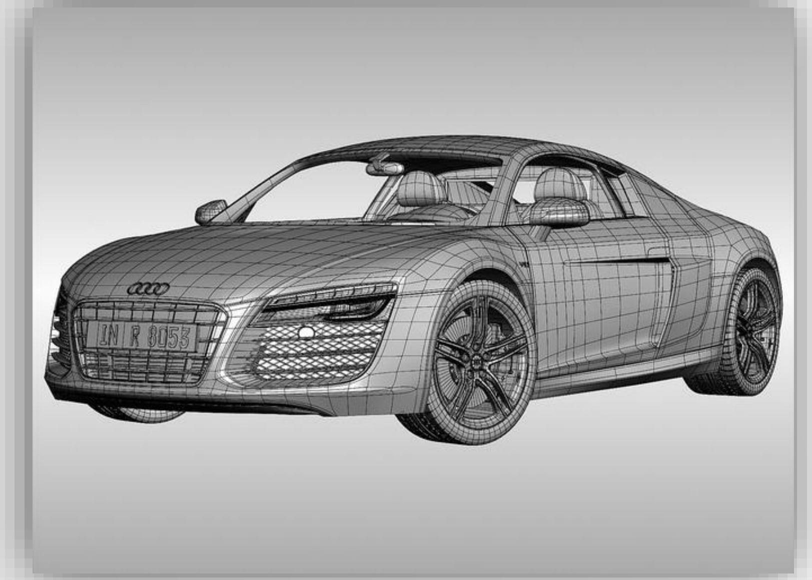
? A waste of time !

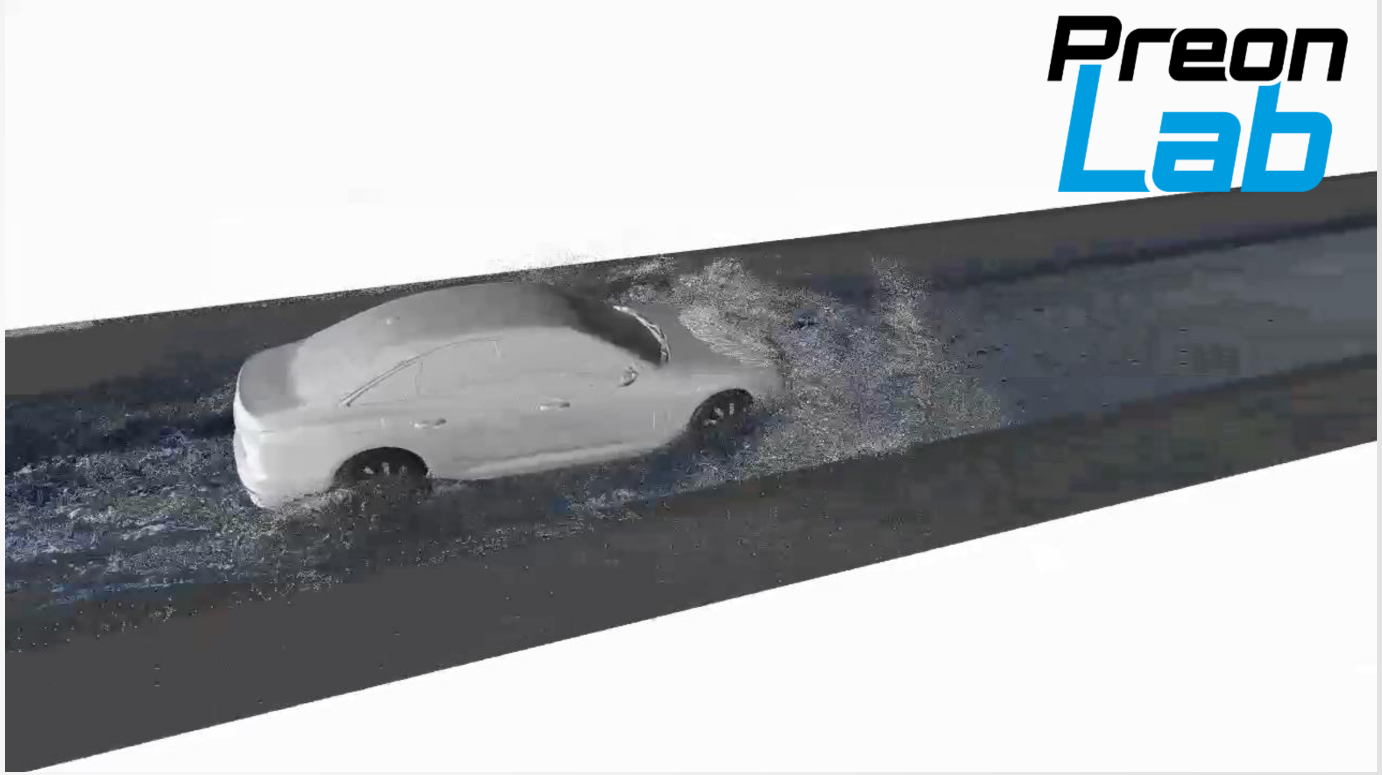
// Purpose of FIFTY2

- **Enable engineers and designers to craft the best version of their product together**
  - Non simulation experts can describe and simulate the problem
  - Easy workflow and fast simulation
  - Results can be monitored and understood by engineers, designers, and decision makers at any time

// Promise

- We build tools that:
  - Reduce time from question to insight (Q2I)
  - Maximize insights: quality and quantity of information
  - Are enjoyable and easy to use





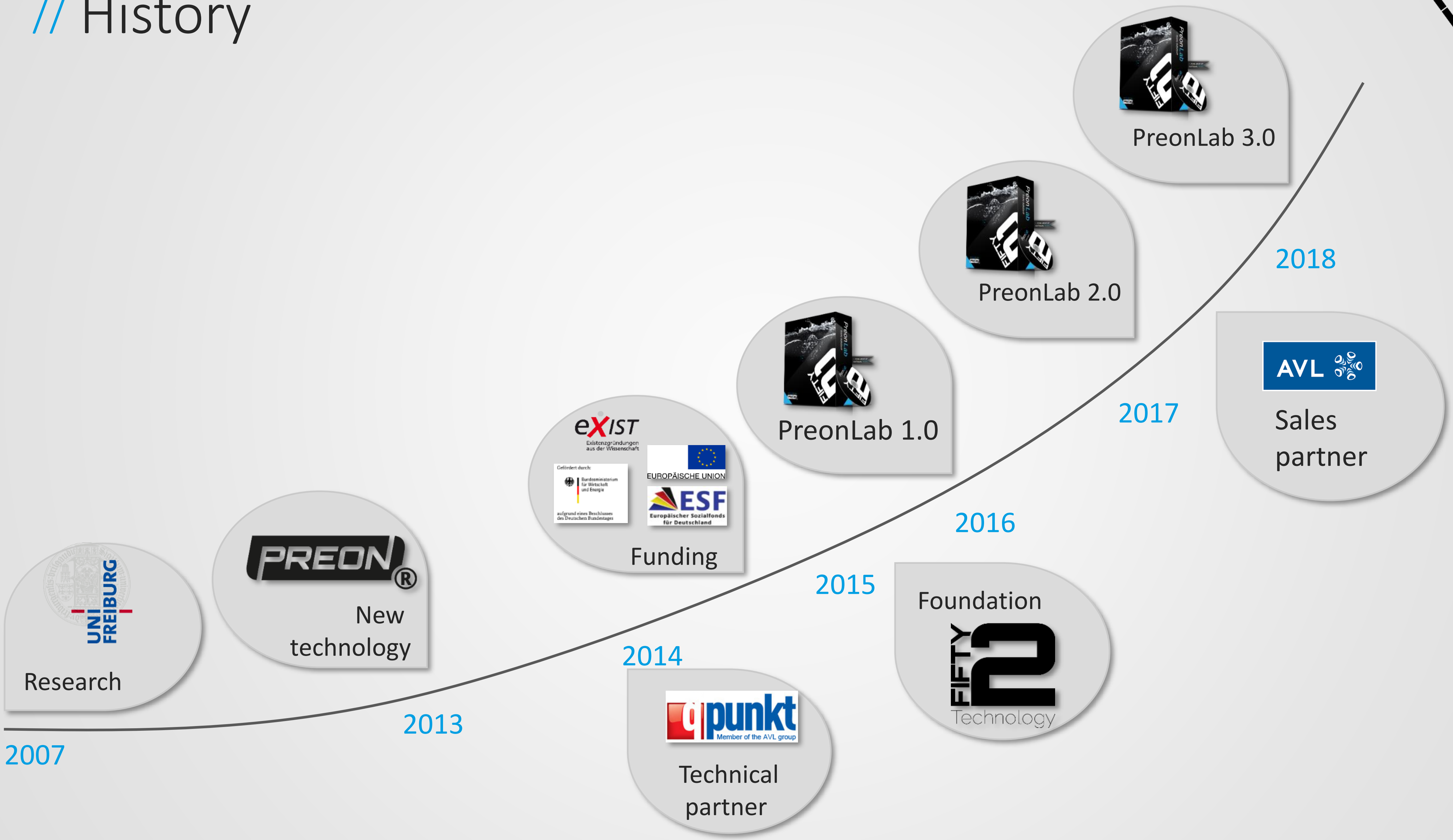
Workflow wading simulation (PreonLab):

Questions
2 hours setup

Days
1 day simulation

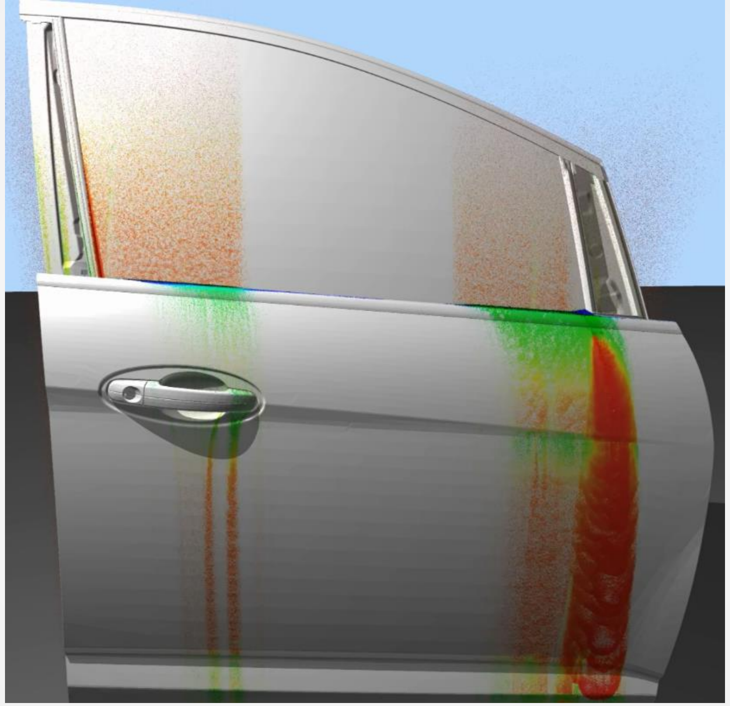
Insights
3 hours analysis

// History

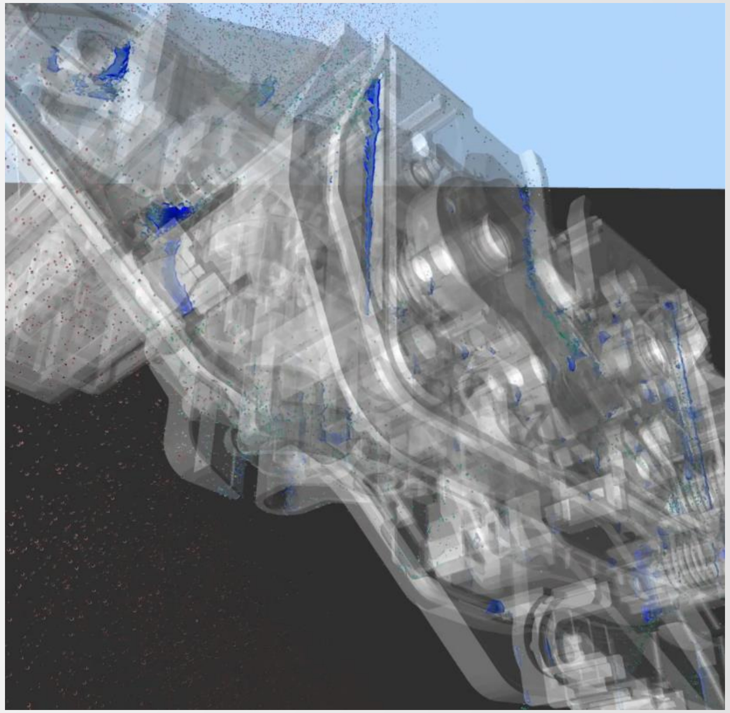

2007
Research
UNI FREIBURG
2013
PREON®
New technology
Funding
EXIST
EUROPÄISCHE UNION
ESF
2014
qpunkt
Member of the AVL group
Technical partner
PreonLab 1.0
2015
Foundation
FIFTY2 Technology
2016
PreonLab 2.0
2017
AVL
Sales partner
PreonLab 3.0
2018

// Watermanagement

Wading

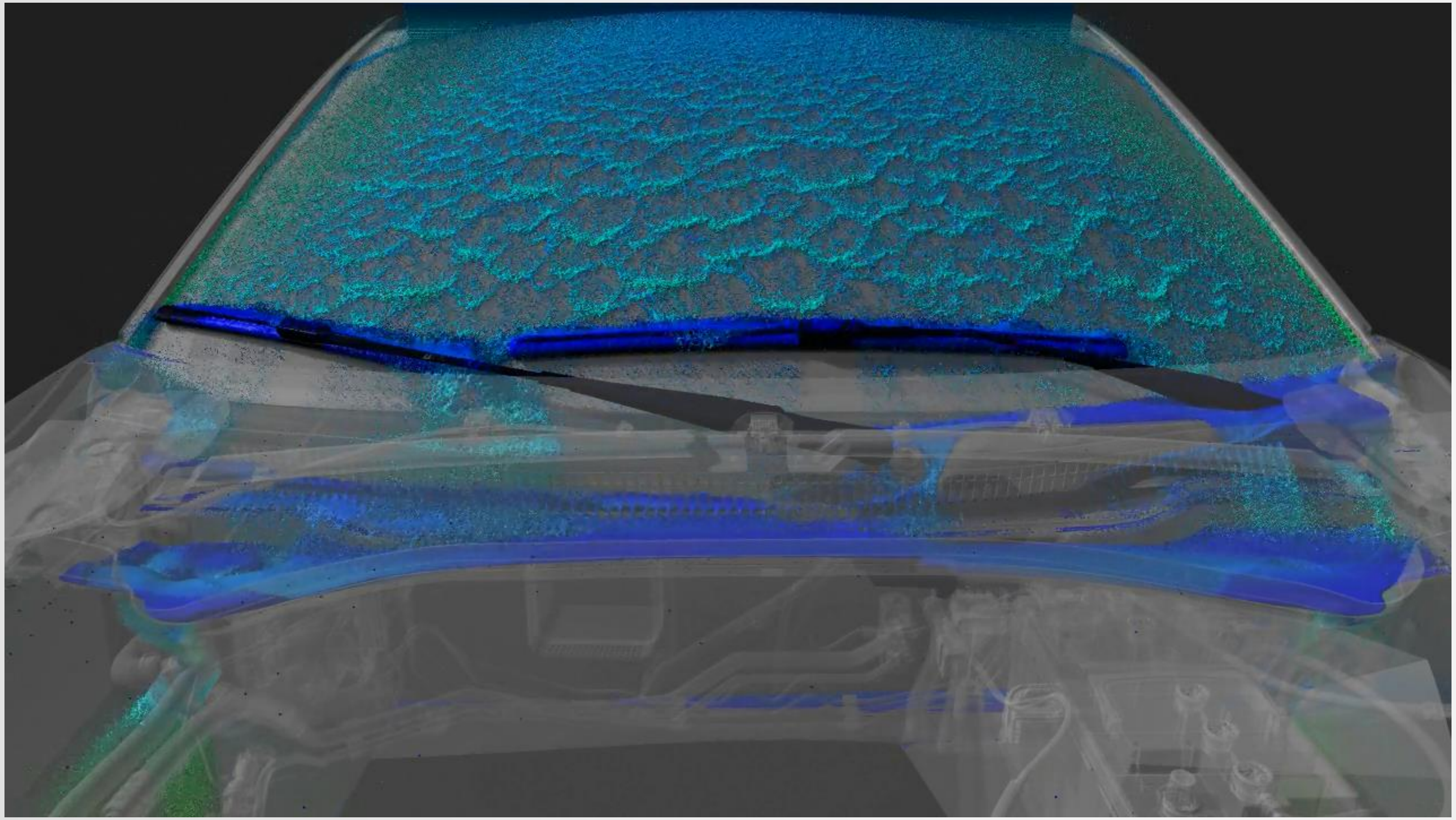


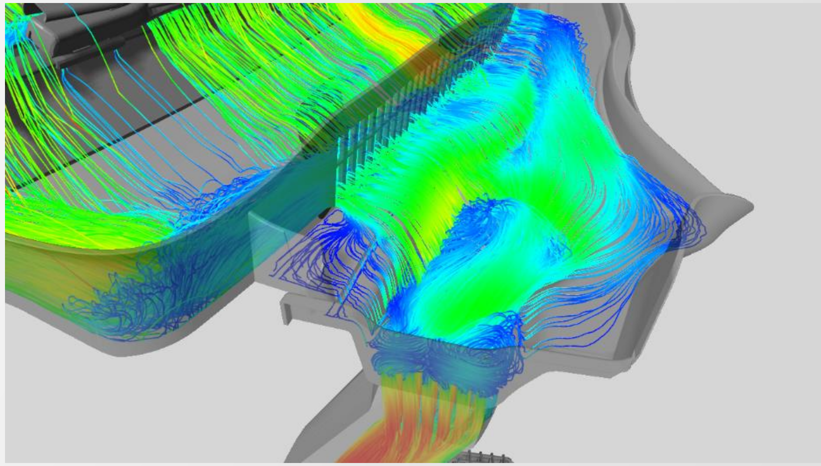
Rain



Corrosion

// Raining



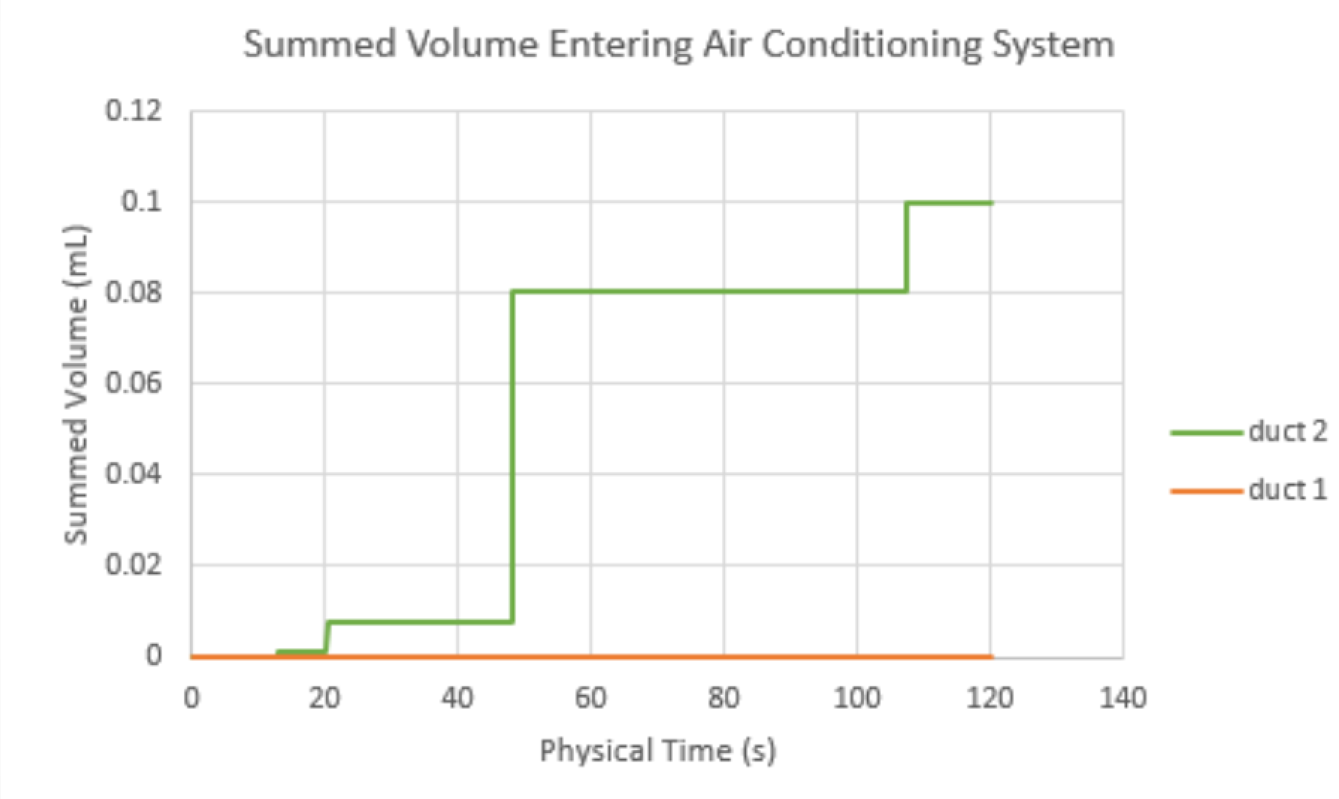


// Raining

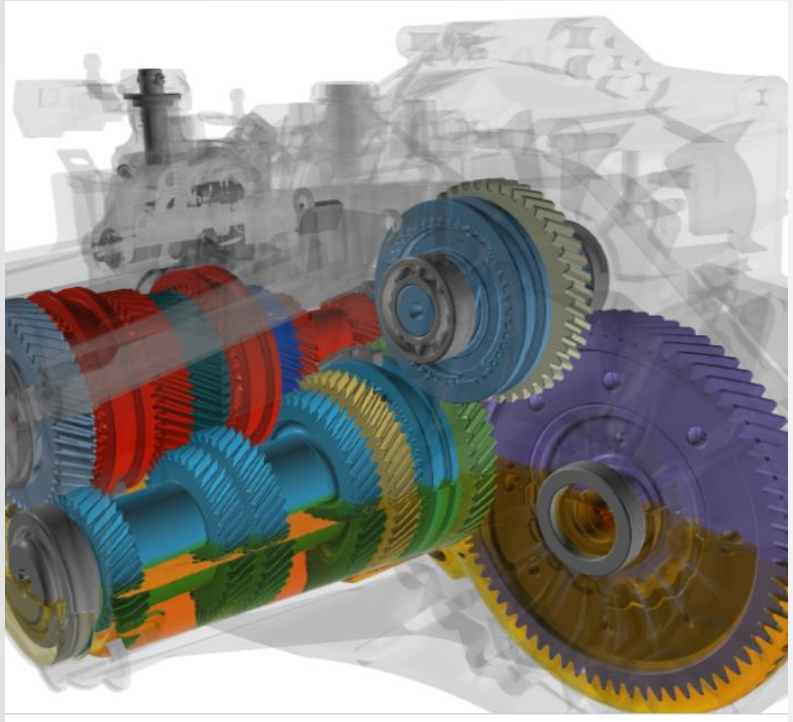
Rapid prototyping:

- Shorter cycles for design testing
- Allows progressive designs

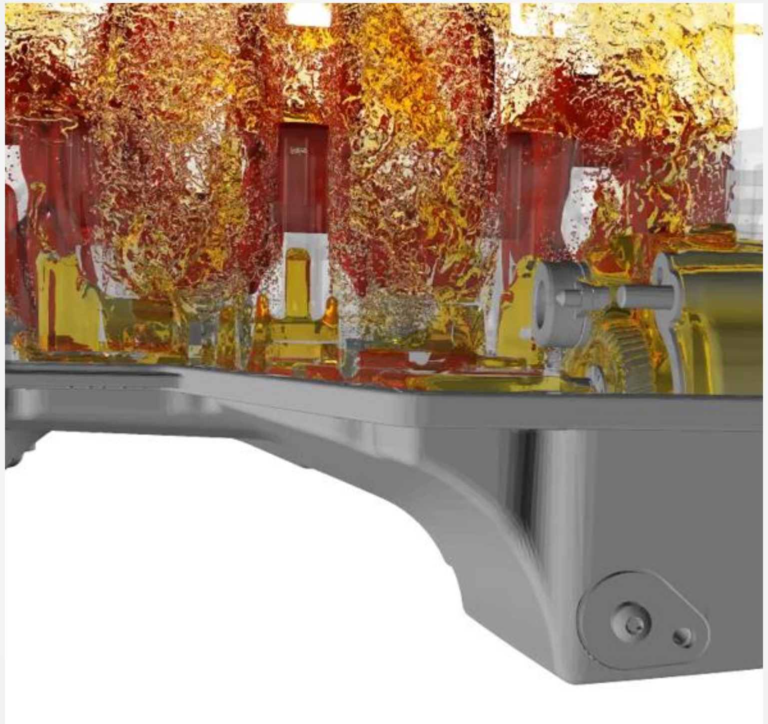
- Duct 2 is a failure
- Continue with duct 1



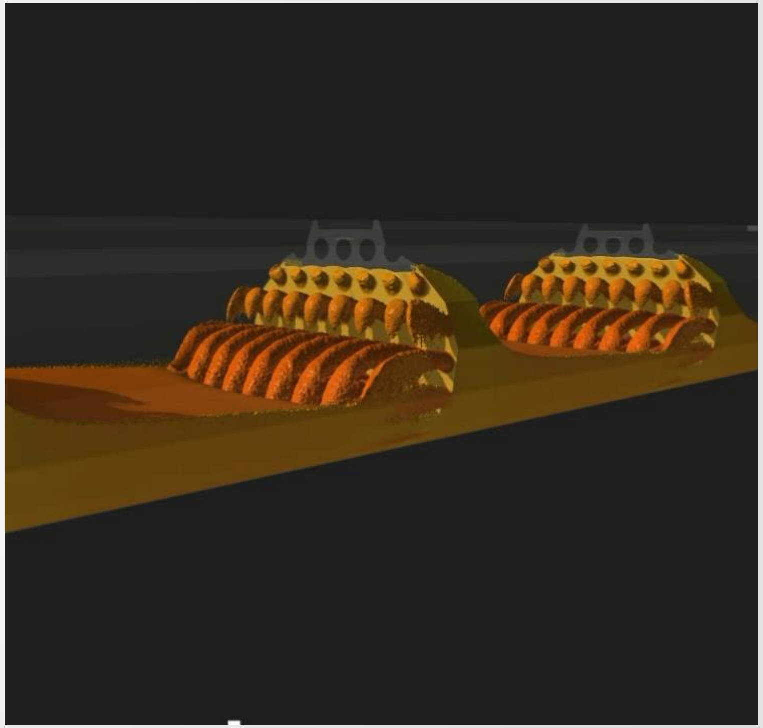
// Oil



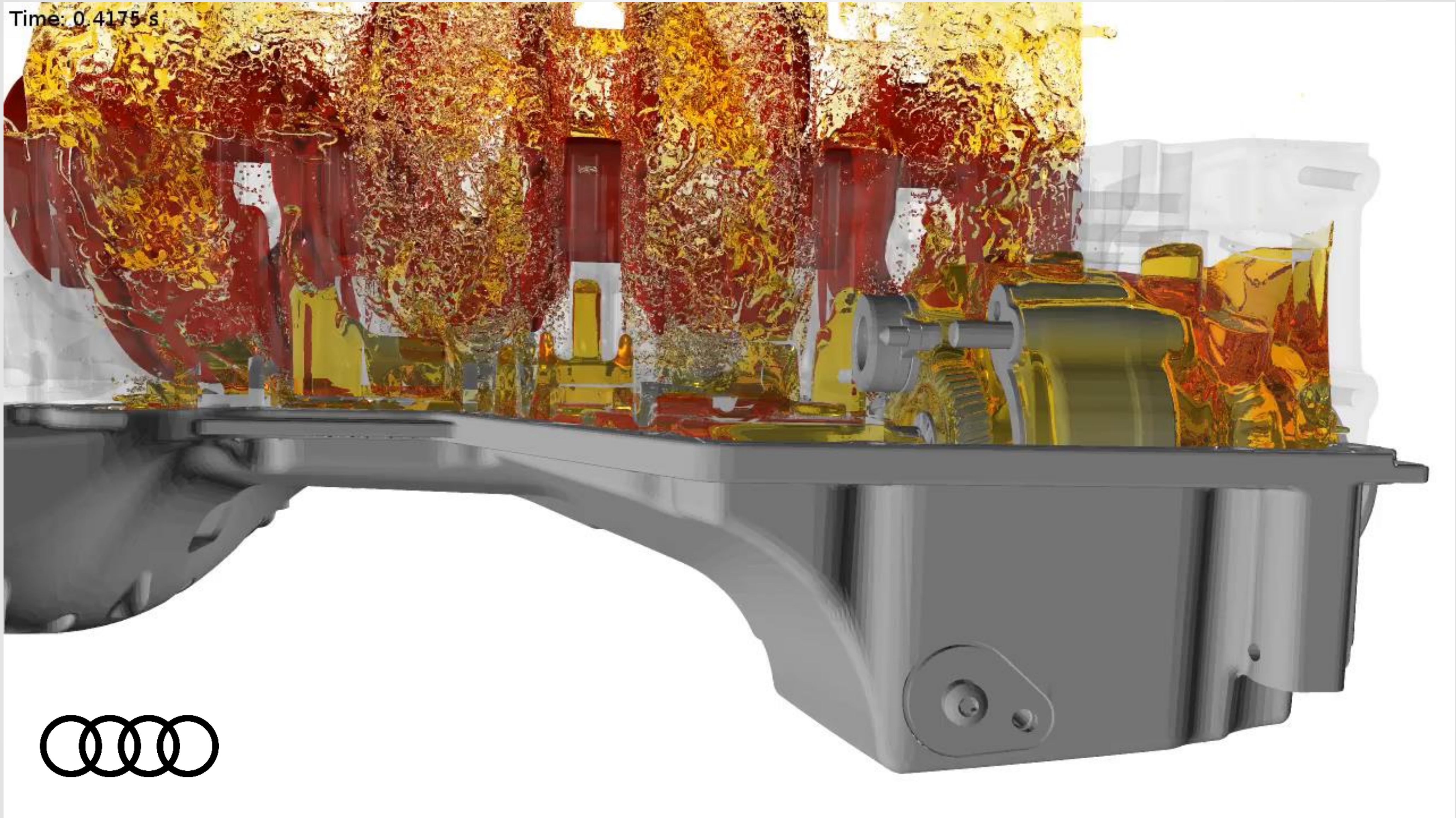
Gear box



Crank Case

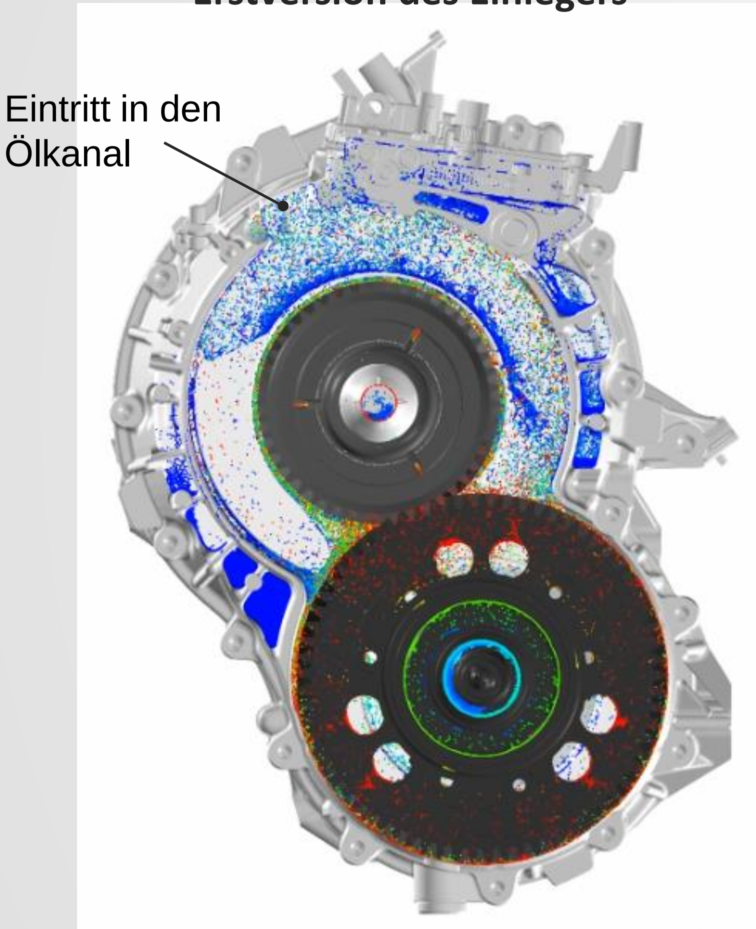


Sloshing

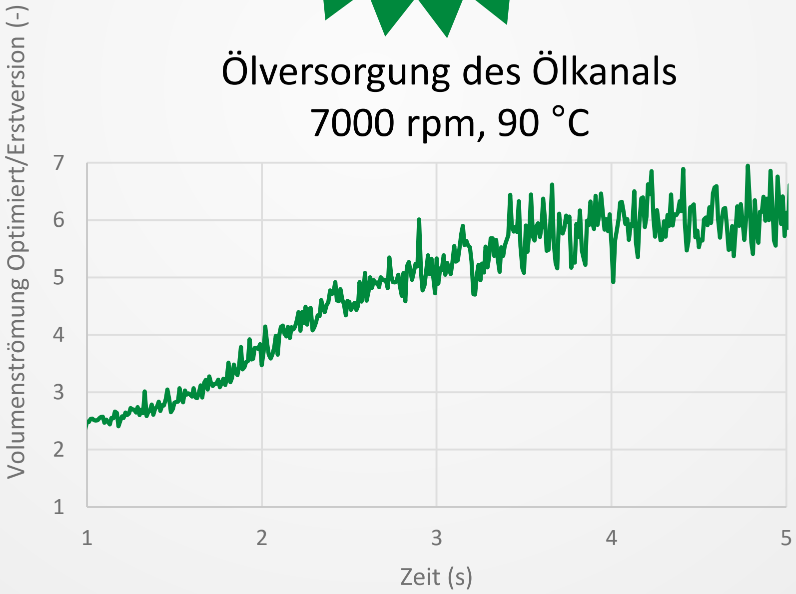

Time: 0.4175 s

// Simulation der Ölverteilung

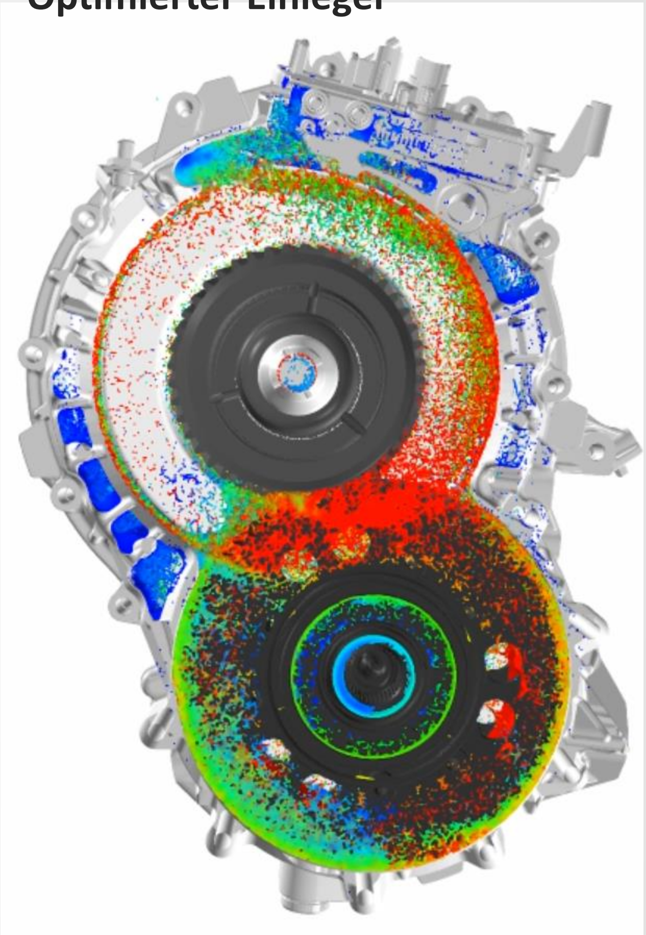
Erstversion des Einlegers



Volumen-
strom 5 bis
6-fach
erhöht



Optimierter Einleger



!

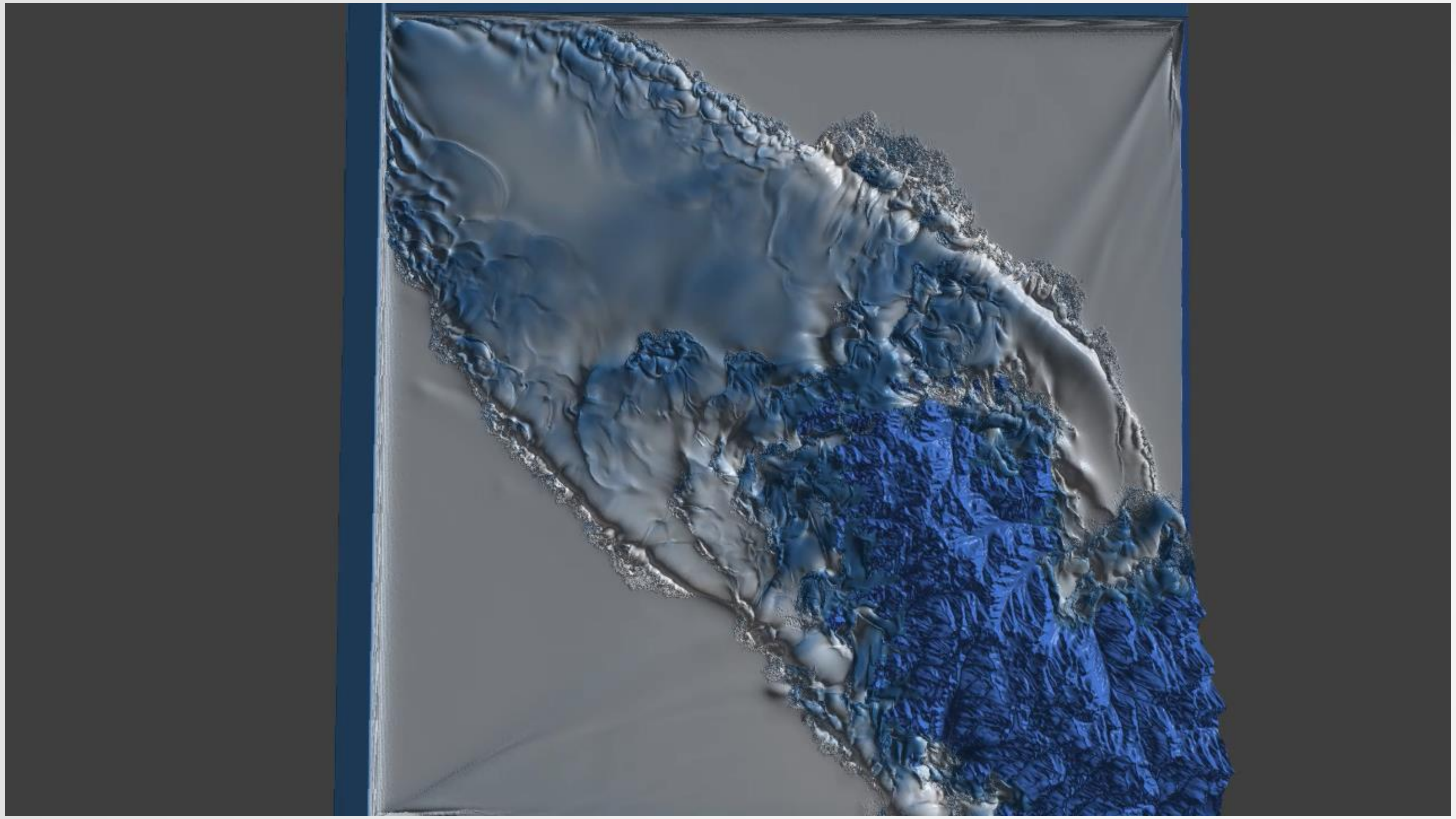
Simulationsergebnisse wurden von Versuchen bestätigt.

// E-machine cooling - Thermodynamics

Particles carry physical quantities, e.g., temperature

// Markets

// Hydraulic engineering



End customer:

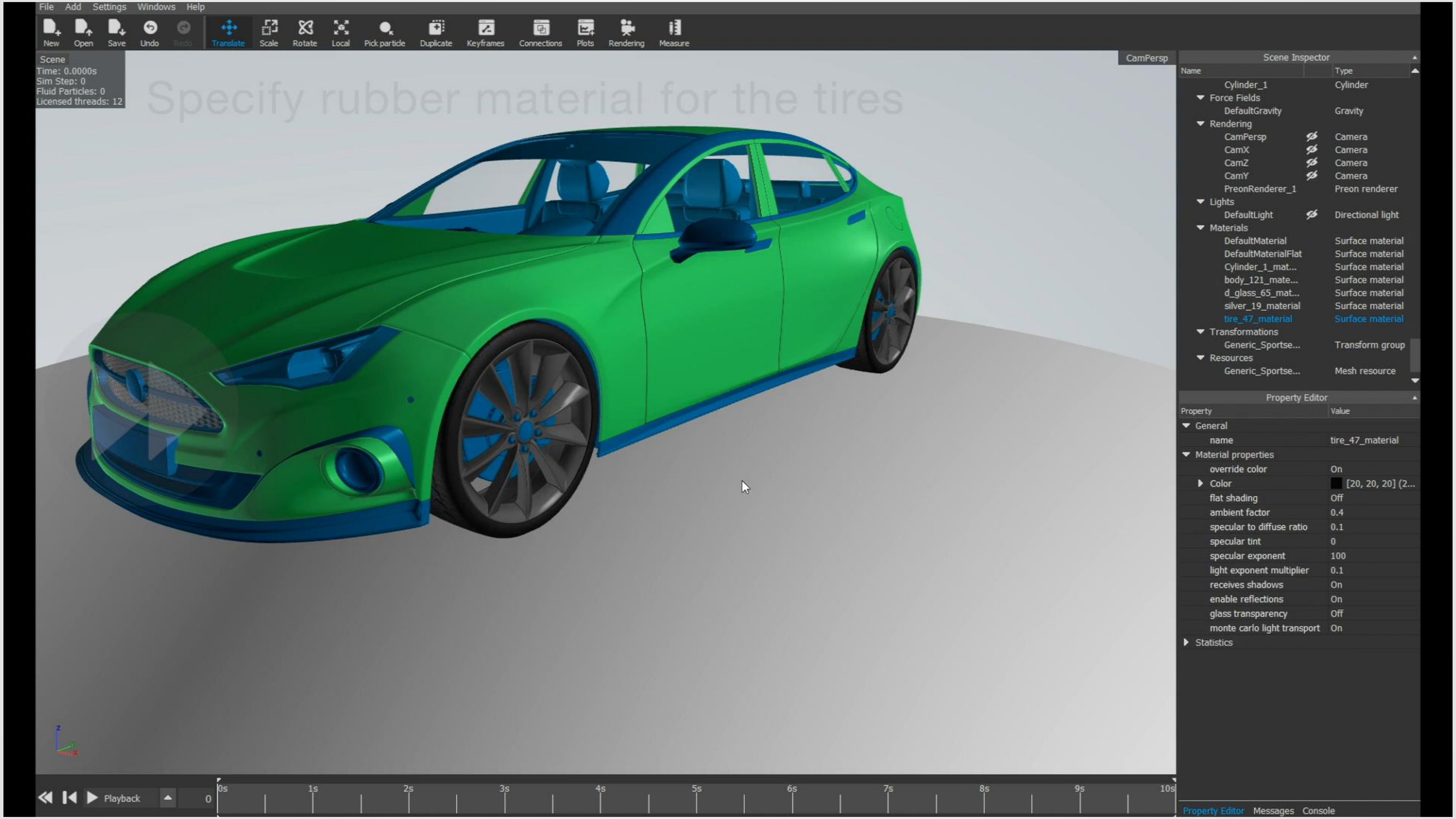
- Governments
- Assurance companies
- City administrations
- Construction companies

TK CONSULT AG
NUMERISCHE MODELLIERUNGEN

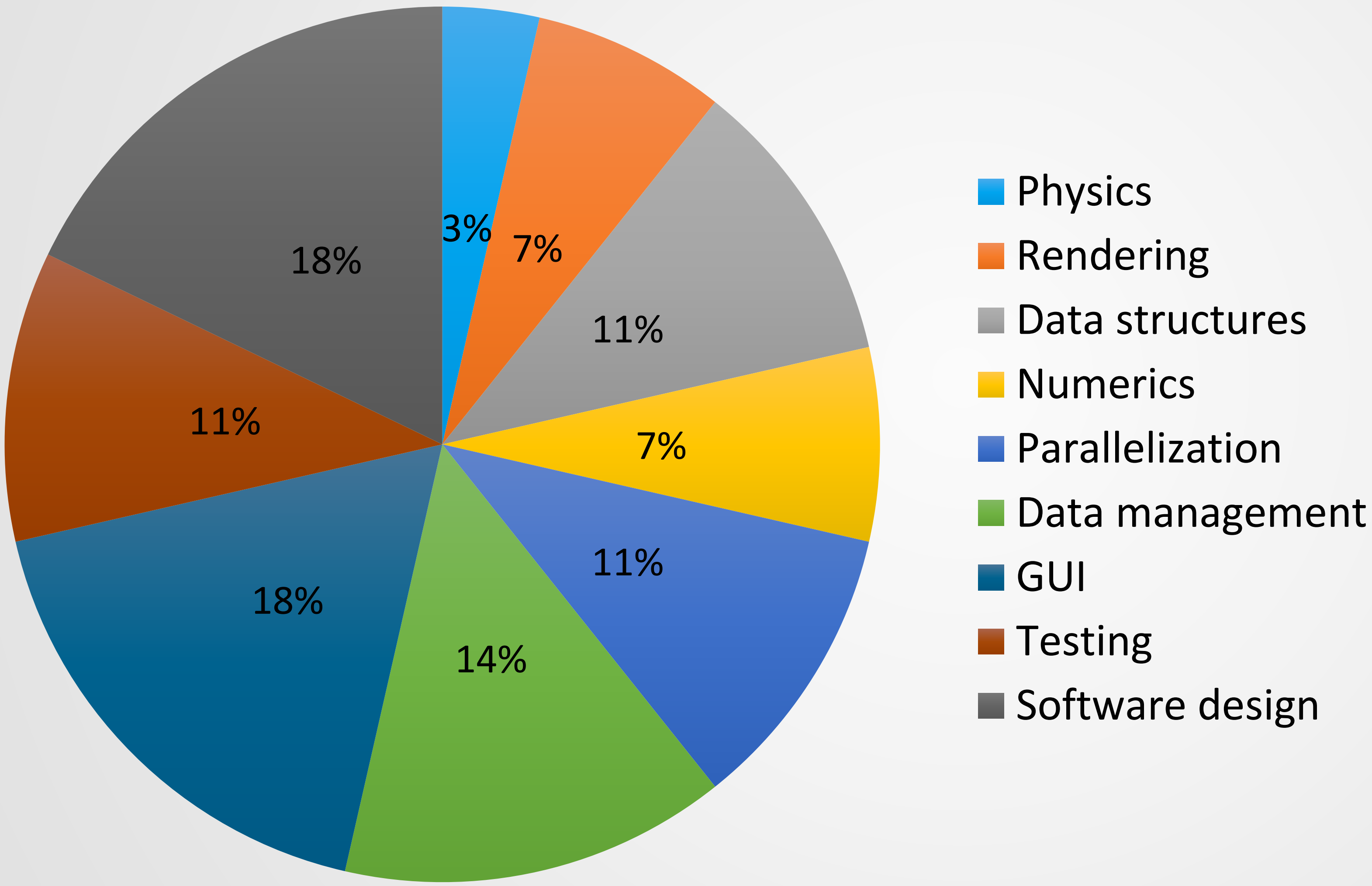
„The future in hydraulic engineering belongs to 3D simulations. Due to its speed and usability, PreonLab has highest chances to be the standard solution in this market.“ (S. Corbe, CEO, TK Consult AG)

Technical and theoretical background

// PreonLab experience



// PreonLab ingredients



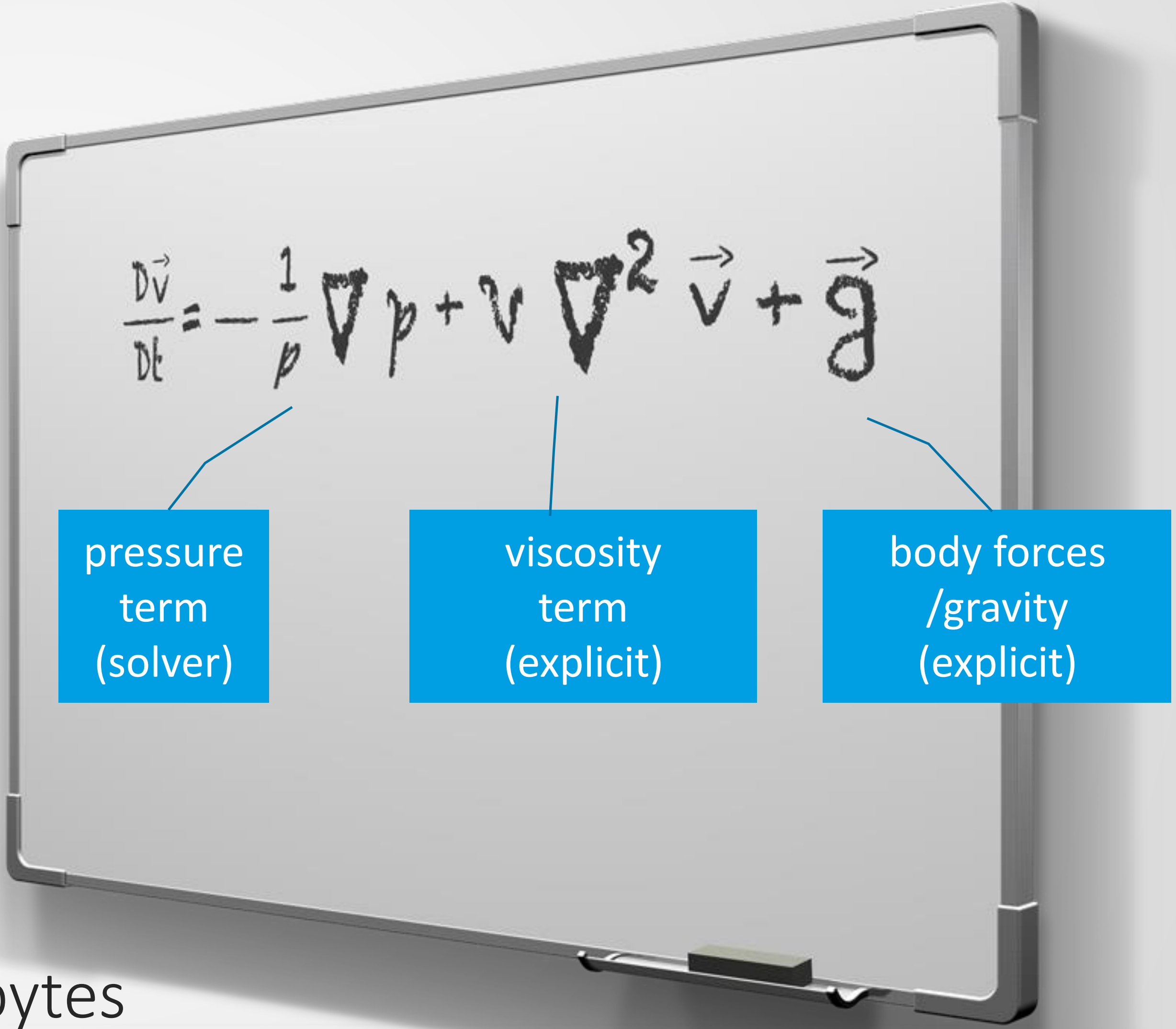
// Fluid simulation

For any point **x** in fluid volume and time t compute position **x**(t). Same for any physical quantity A(**x**,t)

Requires:

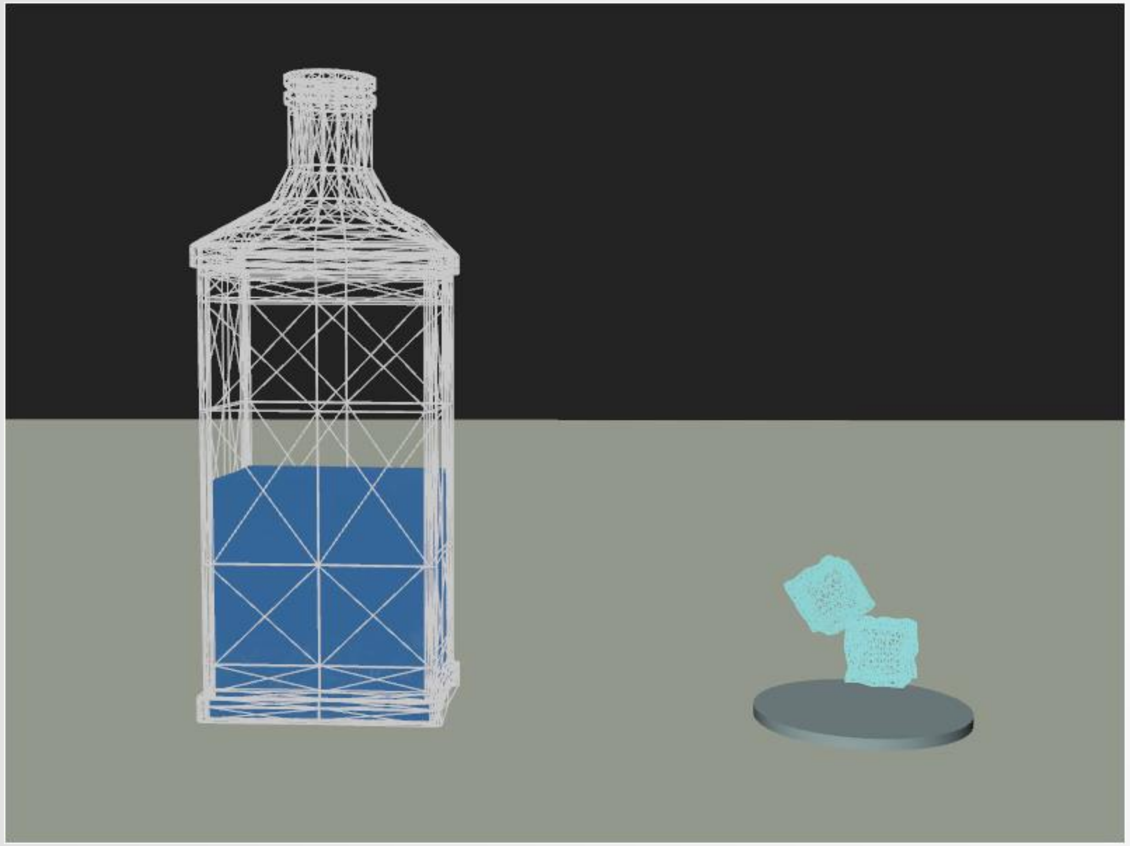
- velocity **v** at any point
- velocity change **dv**

// CFD Solver – Navier-Stokes Equation

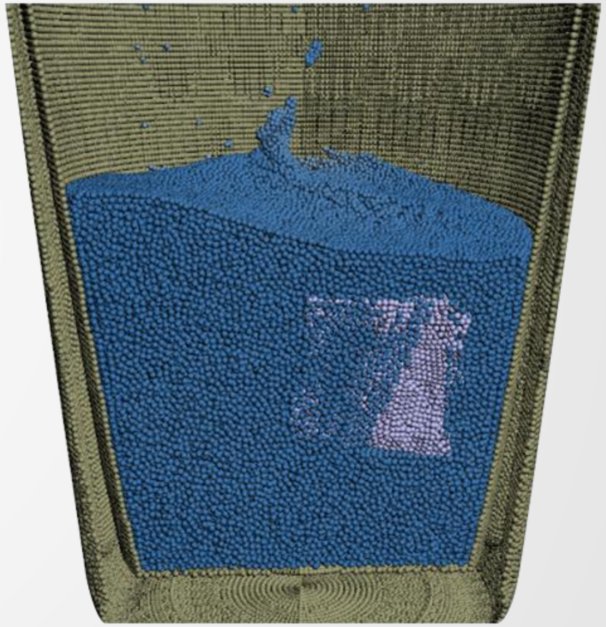


602 billion trillion
molecules per 18ml
250 916 670 000 000 000 terabytes

// Fluid simulation

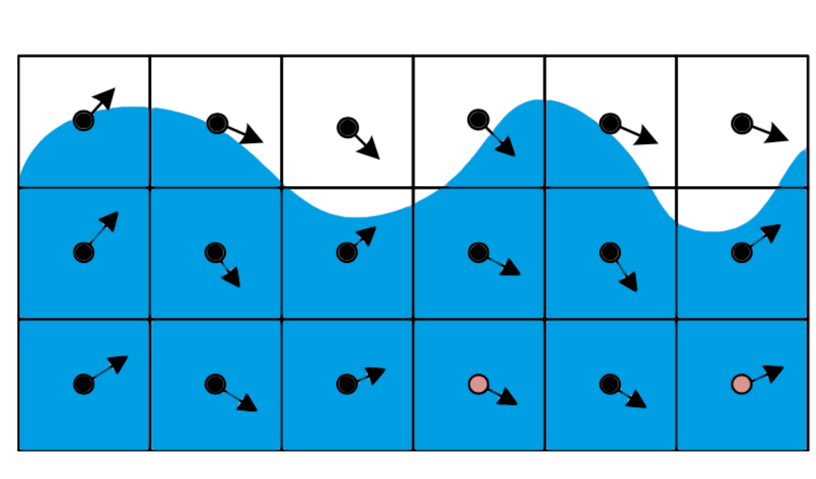


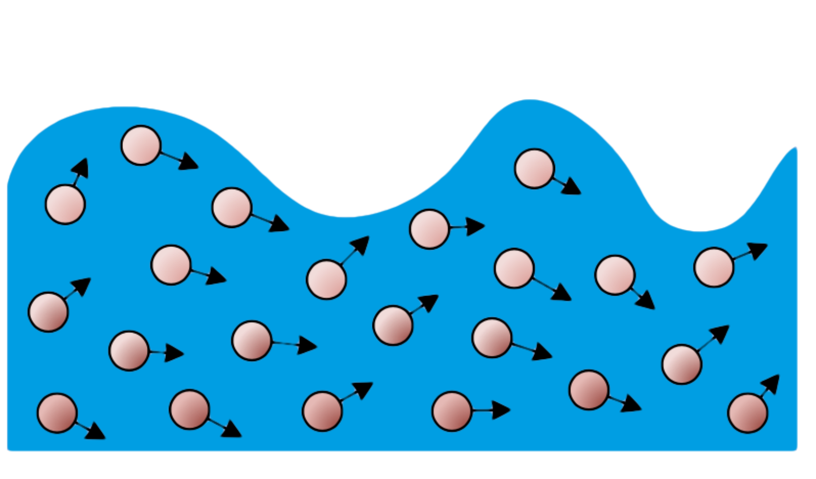
Discretize volume and time



40 megabytes

// Spatial Discretization





- Euler
  - **Grid cells represent partial volumes**

  → Complete domain has to be discretized

  → Spatial derivatives efficiently computed

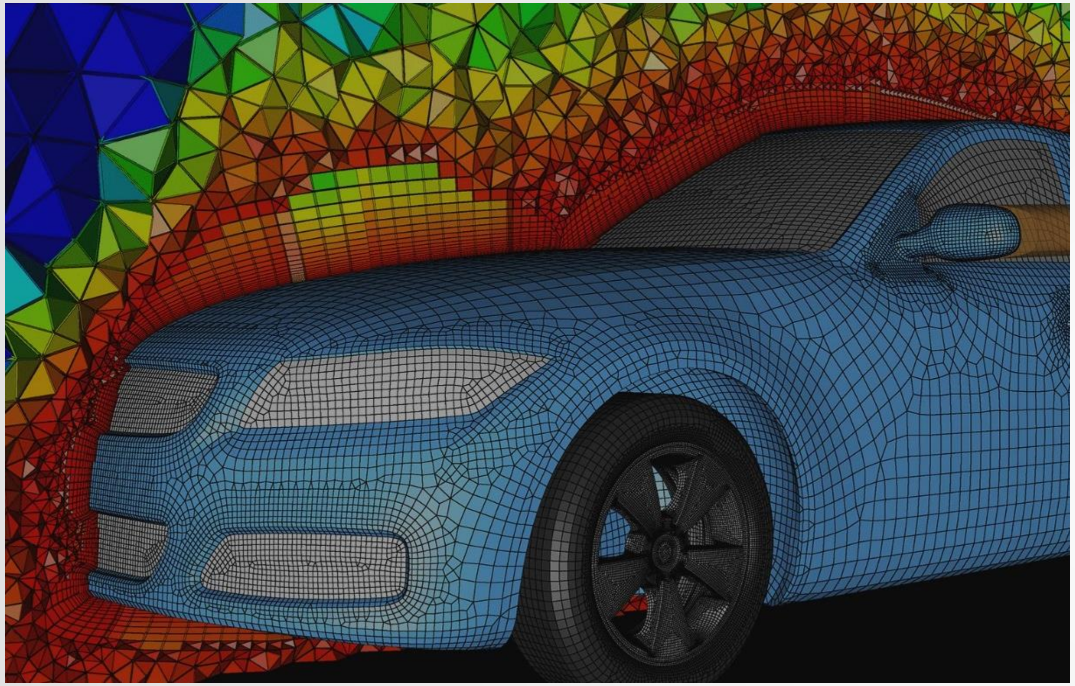
  → Advection expensive to compute
- Lagrange
  - **Particles represent partial volumes**

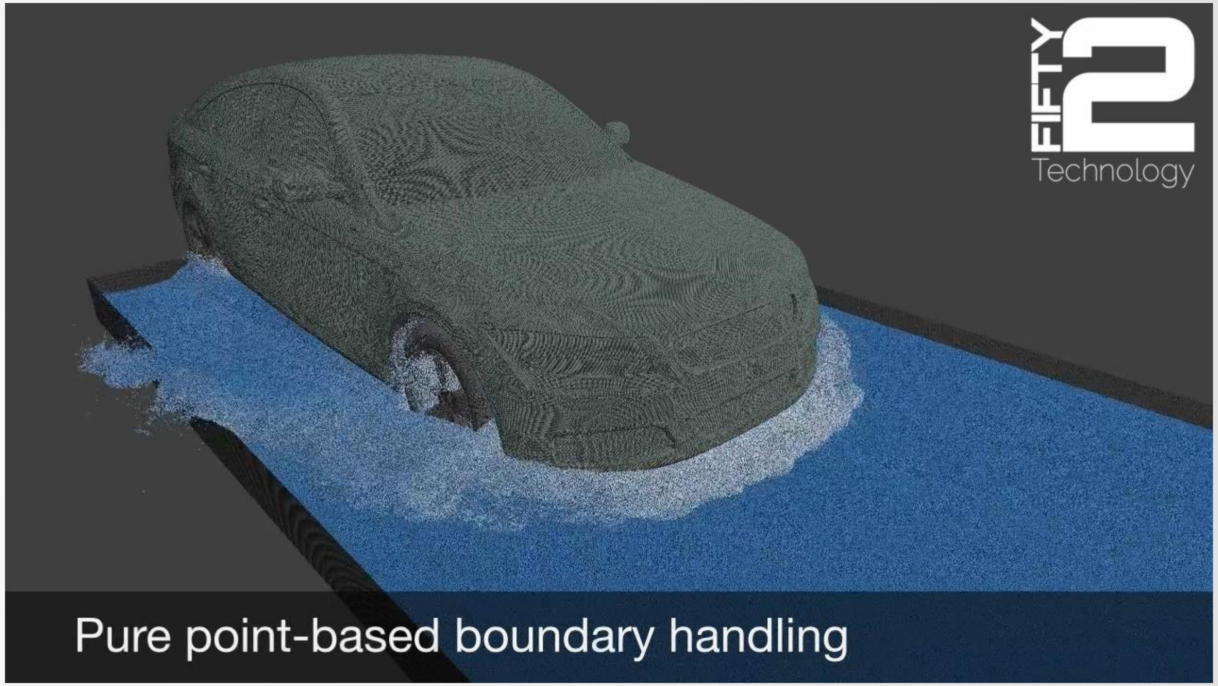
  → Only liquid phase has to be discretized

  → Advection efficiently computed

  → Spatial derivatives expensive to compute

// Spatial Discretization





- Euler
  - **Grid cells represent partial volumes**

  → Align fluid cells with CAD model

- Lagrange
  - **Particles represent partial volumes**

  → Fluid can move arbitrarily and aligns naturally

// Numerical building blocks of a CFD Solver

- **reference frame**: Eulerian, Lagrangian
- **Navier-Stokes equations**: incompressible, compressible
- **spatial derivatives**: FD, FVM, kernel-interpolation
  - FEM, SPH, MPS, FPM, MLS
- **Force term**: implicit, explicit
- **Time-stepping**: implicit, explicit

// Implicit formulation – Discretizing time

$$\underbrace{\frac{\mathrm{D}\mathbf{v}_i}{\mathrm{D}t}}_{\text{acceleration}} = \underbrace{-\frac{\nabla p_i}{\rho_{i,0}}}_{\text{pressure term}} + \underbrace{\nu_i \nabla^2 \mathbf{v}_i}_{\text{viscosity term}} + \underbrace{\nabla \Phi_i}_{\text{surface tension}} + \underbrace{\mathbf{f}_i^{\mathrm{b}}}_{\text{body forces}}$$

1. Explicit calculation of all terms except the pressure term

$$\mathbf{v}_i^* = \mathbf{v}_i + \Delta t \left(\underbrace{\nu_i \nabla^2 \mathbf{v}_i}_{\text{viscosity term}} + \underbrace{\nabla \Phi_i}_{\text{surface tension}} + \underbrace{\mathbf{f}_i^{\mathrm{b}}}_{\text{body forces}} \right)$$

2. Implicit computation of the pressure field

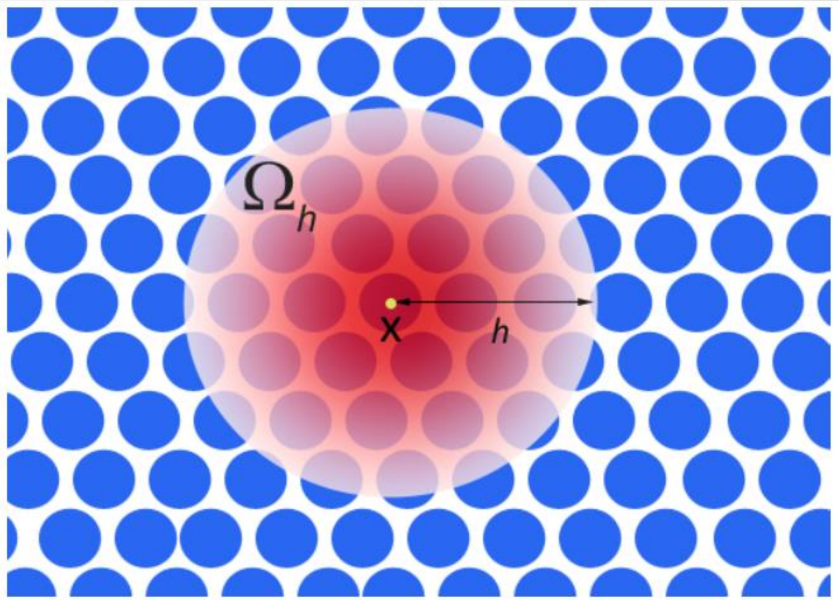
$$\nabla^2 p_i = \frac{\rho_{i,0} - \rho_i^*}{\Delta t^2} \longleftarrow \rho_i^* = \rho_i - \Delta t \rho_{i,0} \nabla \cdot (\mathbf{v}_i^*)$$

$$\mathbf{v}_{i,t+\Delta t} = \mathbf{v}_i^* - \Delta t \frac{\nabla p_i}{\rho_{i,0}}$$

$$\mathbf{x}_{i,t+\Delta t} = \mathbf{x}_i + \Delta t \mathbf{v}_{i,t+\Delta t}$$

// Kernel weighting – Discretizing space

- Value interpolation at position **x**
- Over finite local support domain
- Weighting is color coded
- Rieman sum



$$A(\mathbf{x}) = \int A(\mathbf{x}')\delta(\mathbf{x} - \mathbf{x}')d\mathbf{x}'$$

$$\langle A(\mathbf{x}) \rangle = \int_{\Omega} A(\mathbf{x}')W(\mathbf{x} - \mathbf{x}', h)d\mathbf{x}'$$

$$\langle A(\mathbf{x}_i) \rangle = \sum_j V_j A(\mathbf{x}_j)W(\mathbf{x}_i - \mathbf{x}_j, h)$$

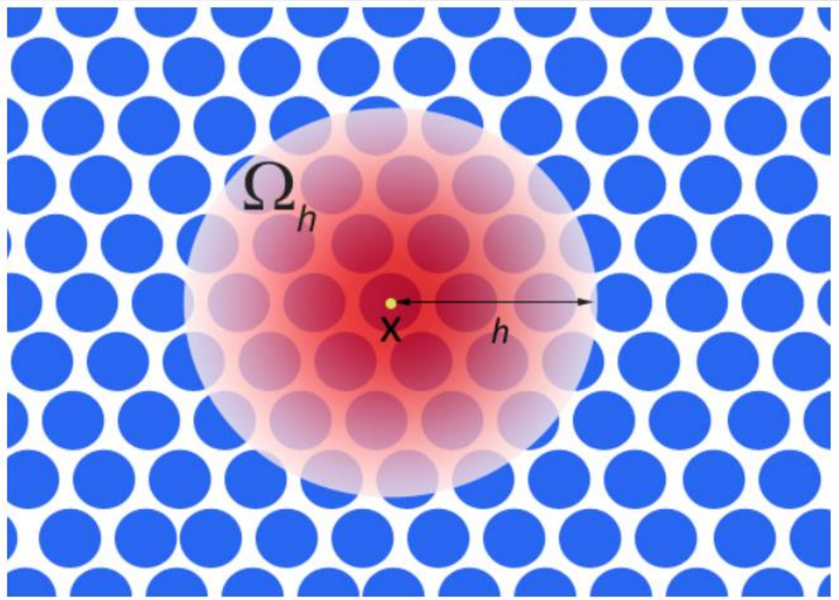
// Simulation loop

1. Find neighbors
2. Compute explicit forces
3. Solve for implicit forces
4. Update velocities, positions and other physical quantities of partial volume (particles)

// Performance – Neighbor search

- Typically 30 to 40 particles in influence domain
- 1 million particles: 20ms

- Reduce number of queries
  - Compact hashing
  - Z-index sorting
  - kd-trees



// Performance – System of equations

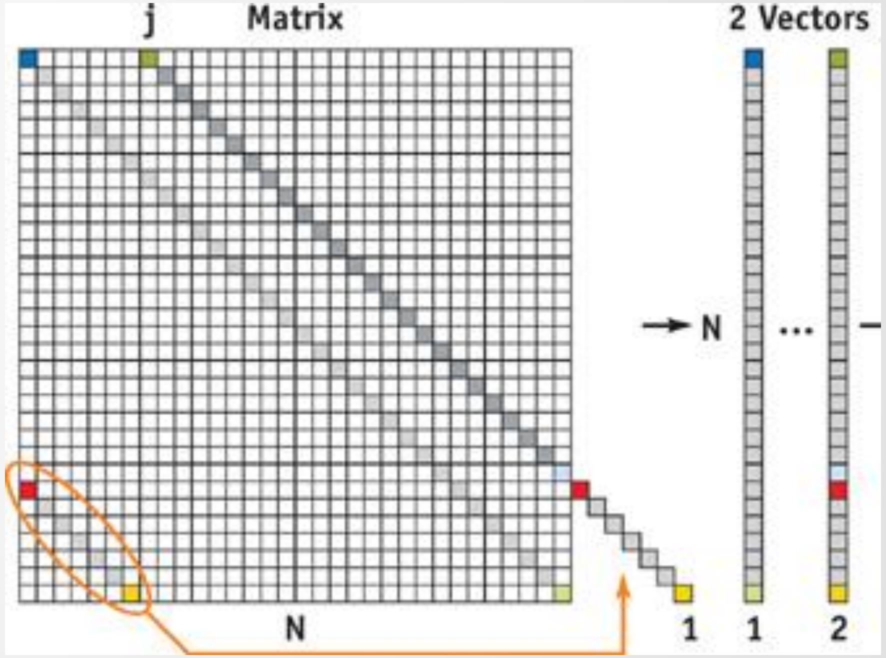
- Pressure term
  - Enforce volume conservation of fluid
  - Solve for unknown pressure field
  - Pressure gradient results in forces
- Viscosity term
  - Minimize strain-rate tensor
  - Changes the velocity gradient

$$\mathbf{D} = \frac{1}{2}(\nabla\mathbf{v} + (\nabla\mathbf{v})^T)$$

// Performance – System of equations

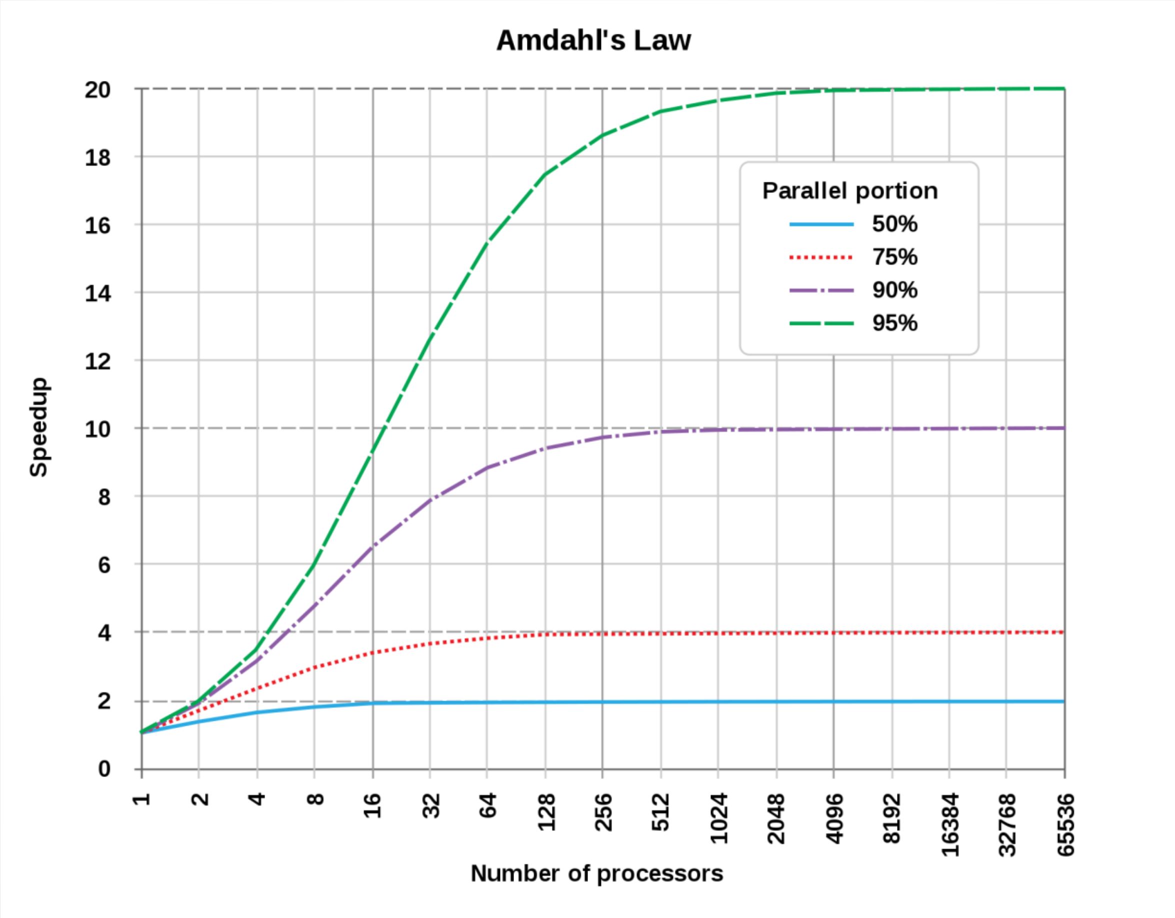
- Simulation with 100 million particles
- Linear system of size 100M x 100M
  - Conjugate gradient
  - Relaxed Jacobi
  - Gauss-Seidel
- System is sparsely filled
  - Matrix-free and compact implementation

$$\mathbf{A}\mathbf{x} = \mathbf{b}$$



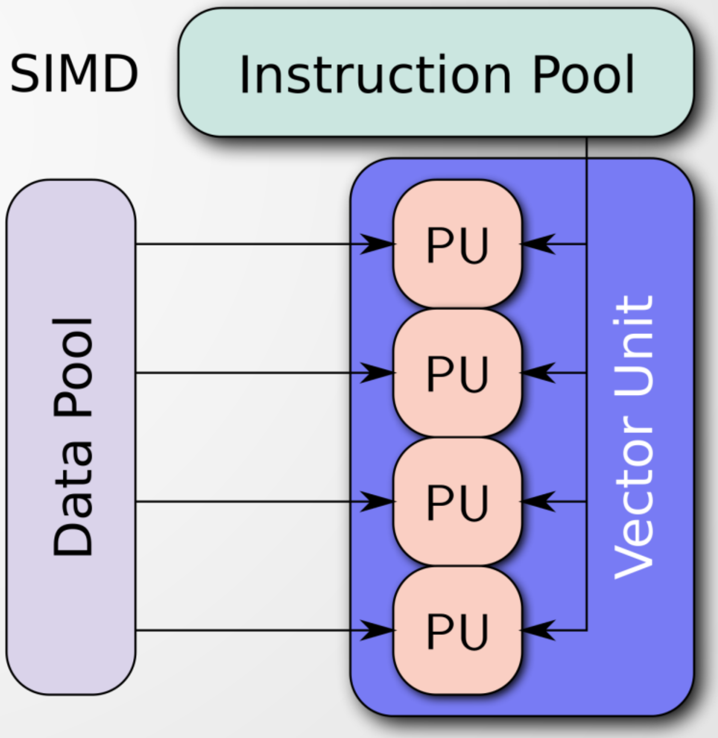
// Performance - Parallelization

- Expectable speed-up obeys Amdahl‘s law



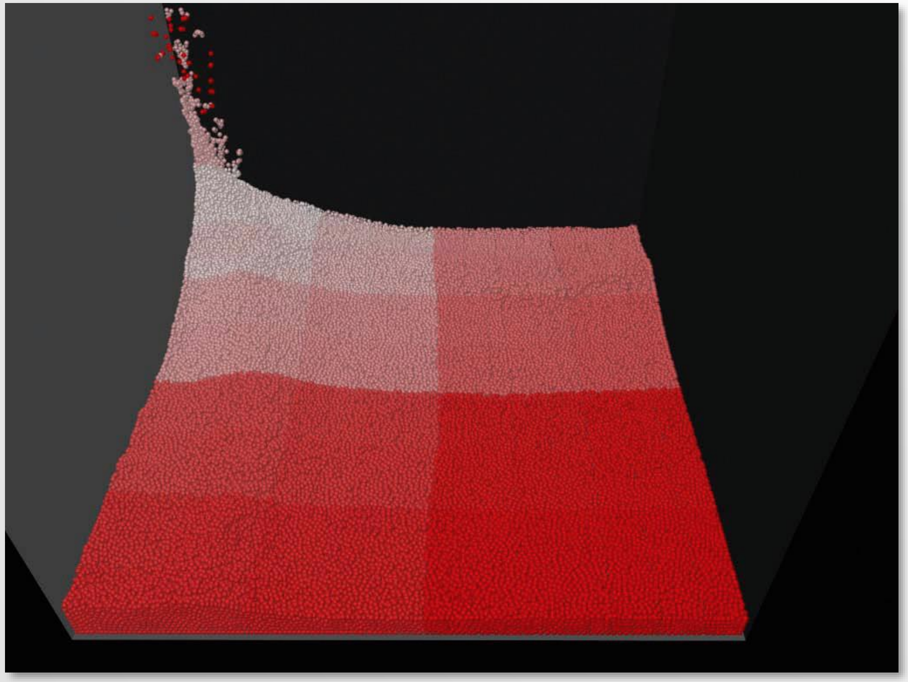
// Performance - Parallelization

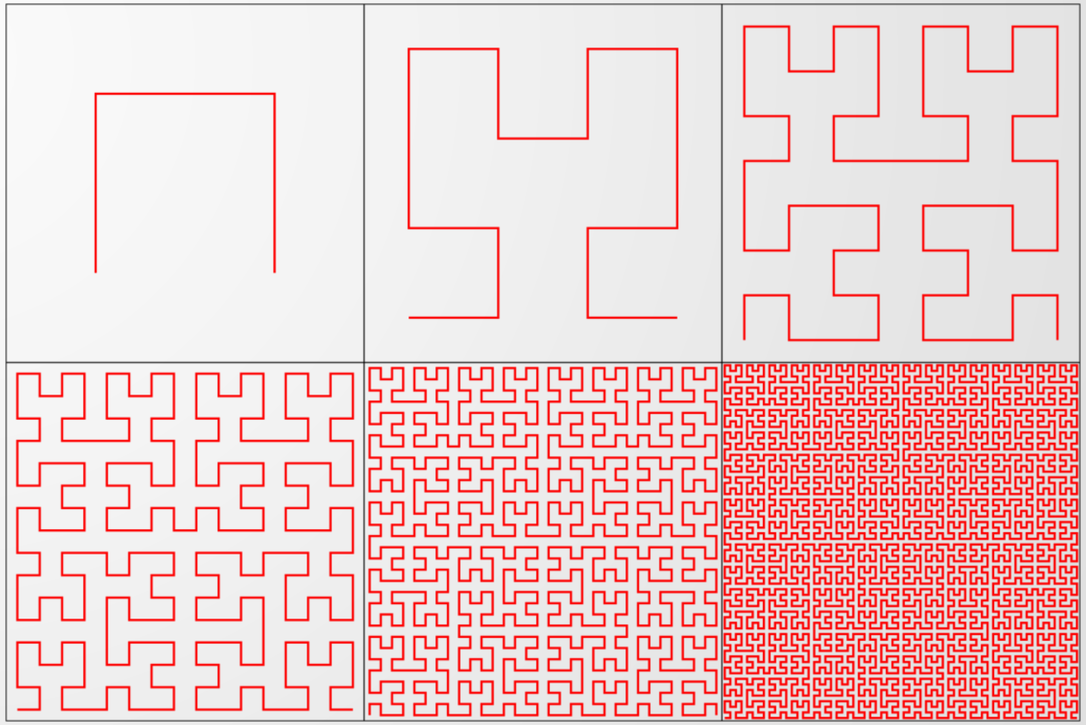
- Expectable speed-up obeys Amdahl‘s law
- Reduce latencies
  - SIMD: Optimized data structures



// Performance - Parallelization

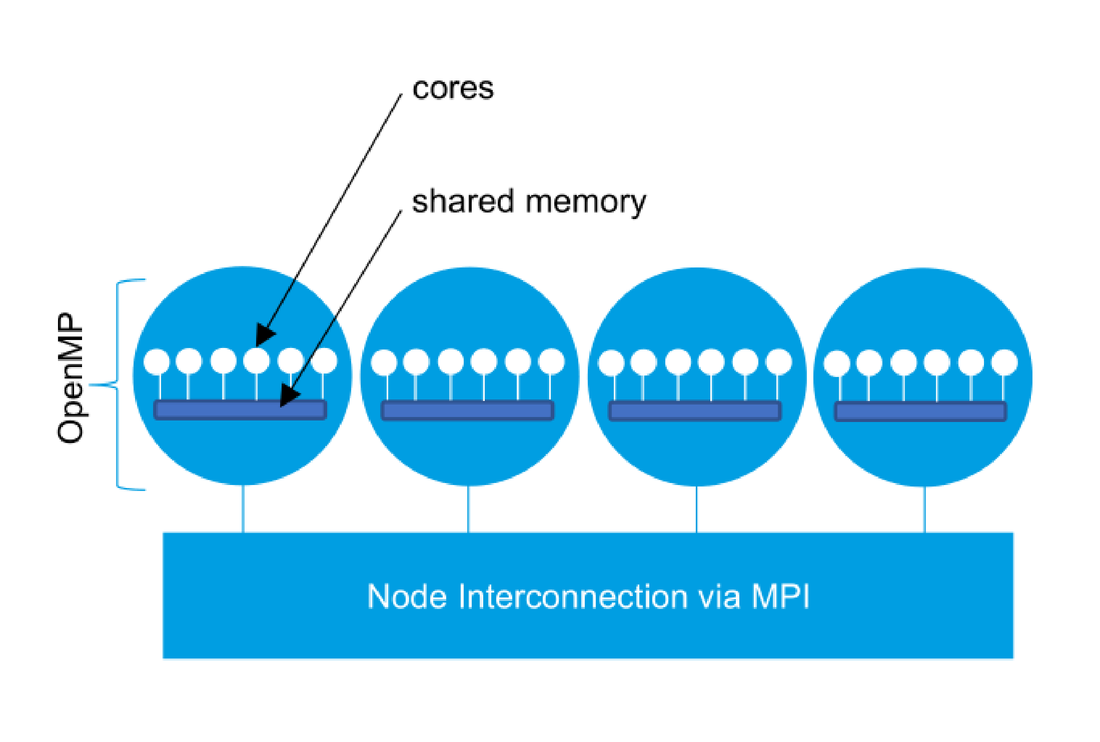
- Expectable speed-up obeys Amdahl's law
- Reduce latencies
  - Single Instruction Multiple Data
  - SMP: Increase cache coherency





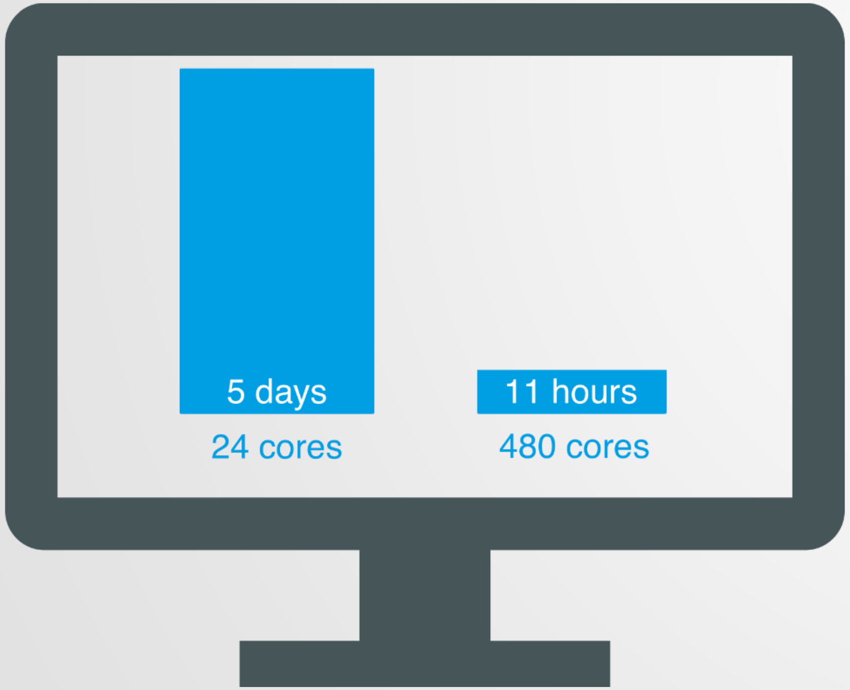
// Performance - Parallelization

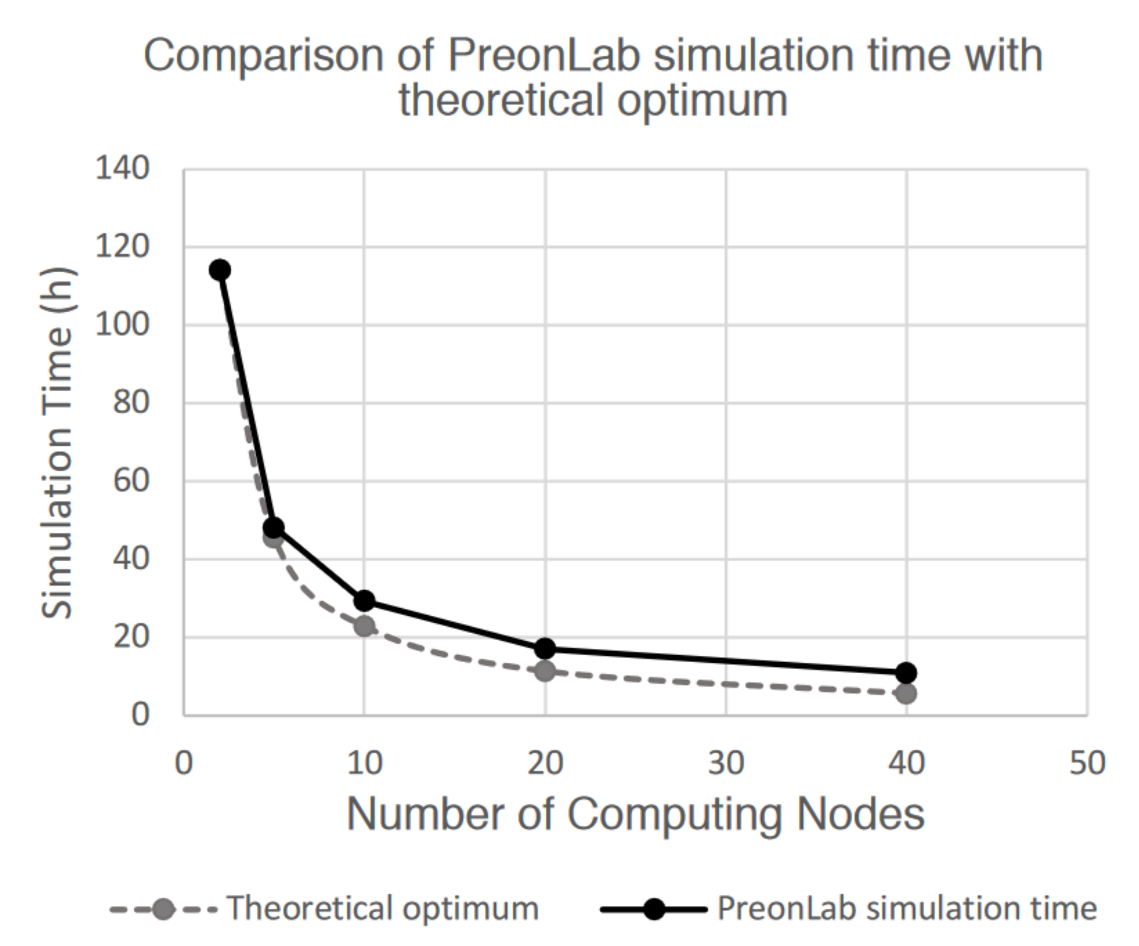
- Expectable speed-up obeys Amdahl‘s law
- Reduce latencies
  - SMP: Increase cache coherency
  - SIMD: Optimized data structures
  - MMP: Load balancing



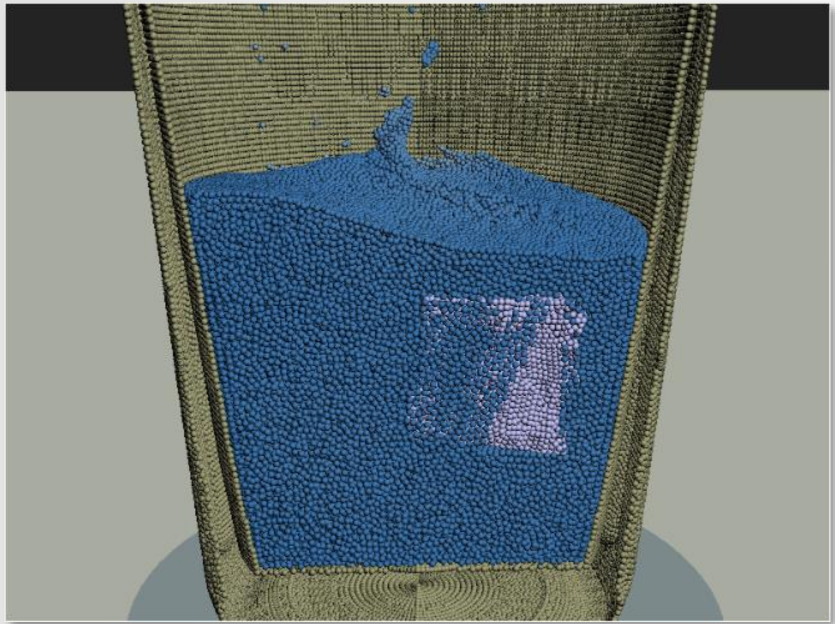
// Performance – Hybrid parallel implementation

73500 liter
157 Million particles
40 sec





// Rendering



Simulation:

- Discrete representation

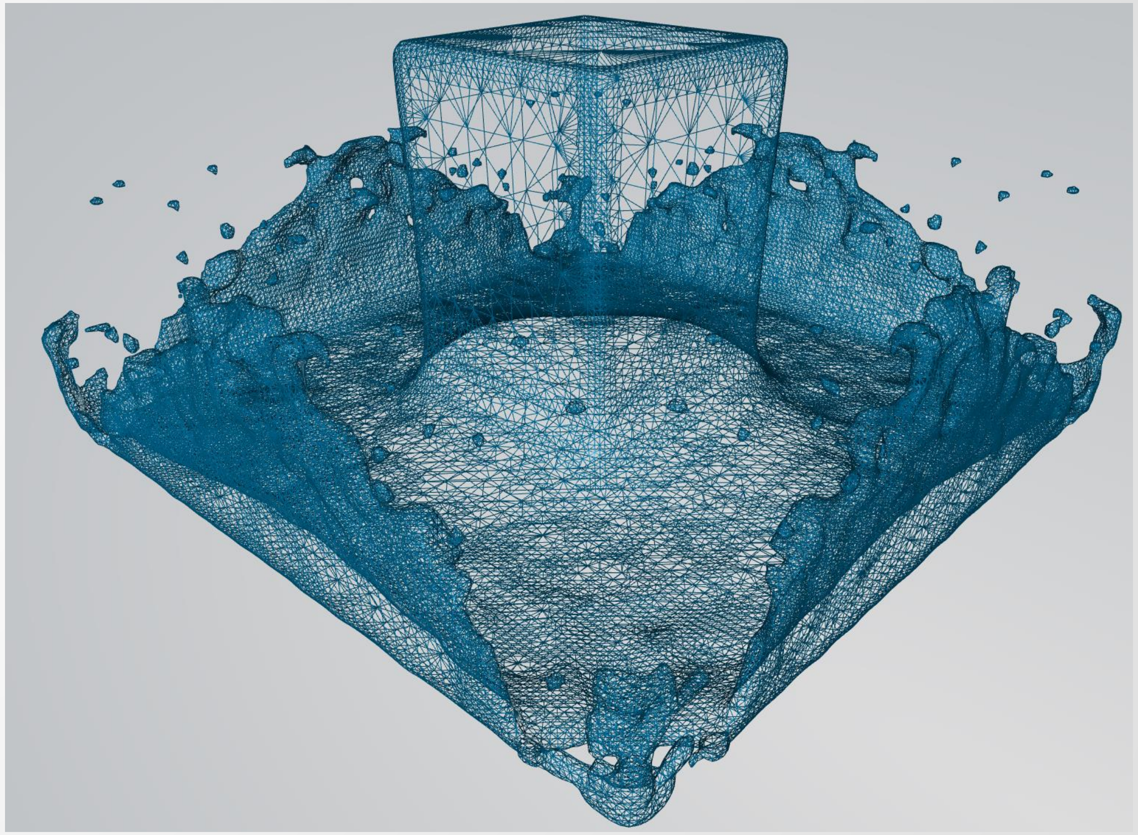
Visualization:

- Continuous volume
- Simulate absorption, reflection and transmission of light

// Classical approaches

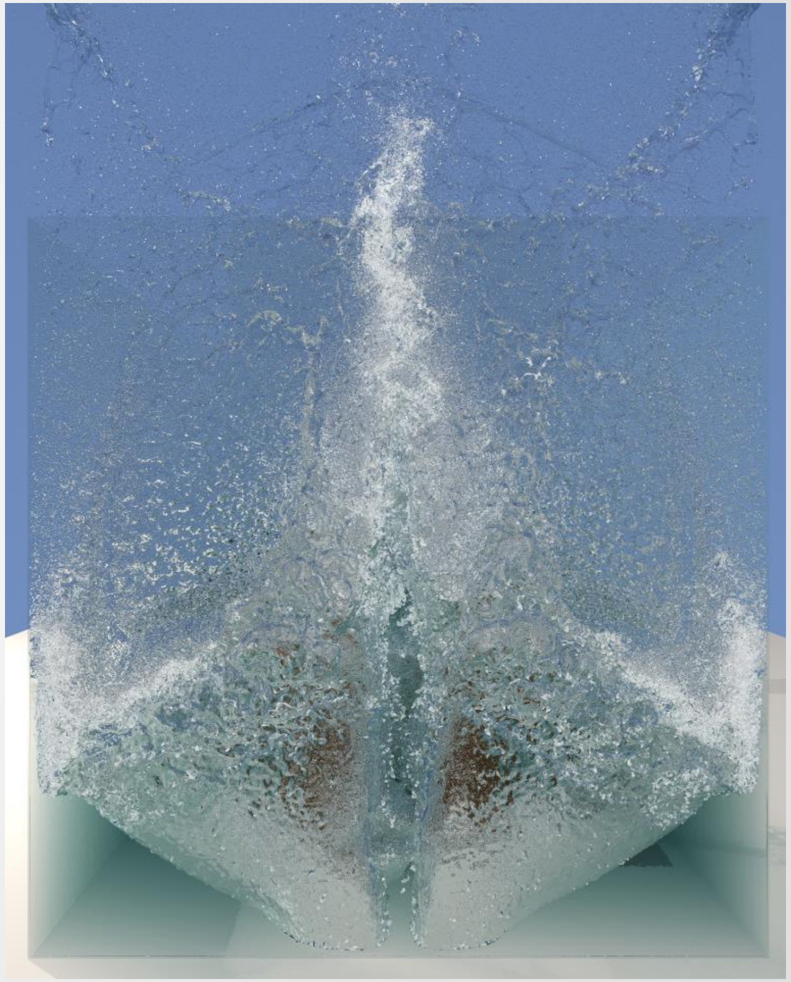
- Create triangle mesh from particles
- Isosurface generation via
  - Marching cubes
  - Dual contouring
  - Adaptive dual marching cubes

- Mesh files can be used
  - By any raytracing program
- But
  - Time-consuming to construct
  - Consume a lot of memory



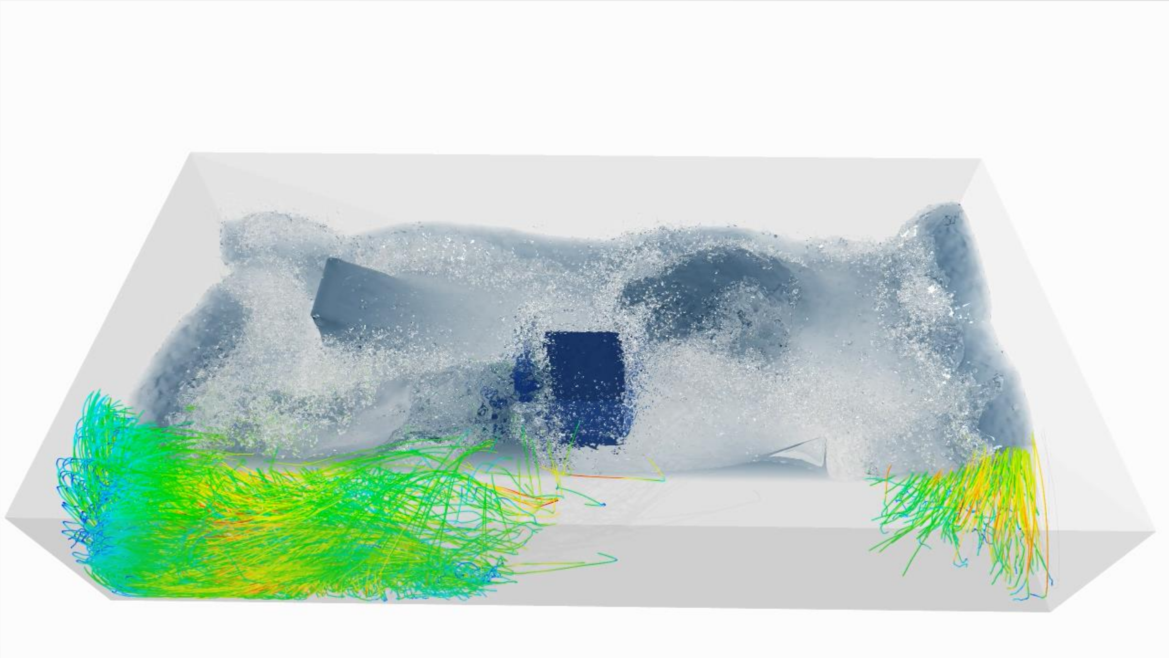
// Preon renderer

- Renders fluid as smooth surface without generating an explicit mesh
- CPU-based ray tracer which works on systems without graphic cards / cluster
- Fast generation by using neighbor search data structure
- Implicit foam rendering
- Output is image per frame



// Preon renderer

- Physically-based stochastic raytracer
- Photon mapping
- Fluid properties can be colorized on virtual surface and sensors can be visualized



What‘s next?

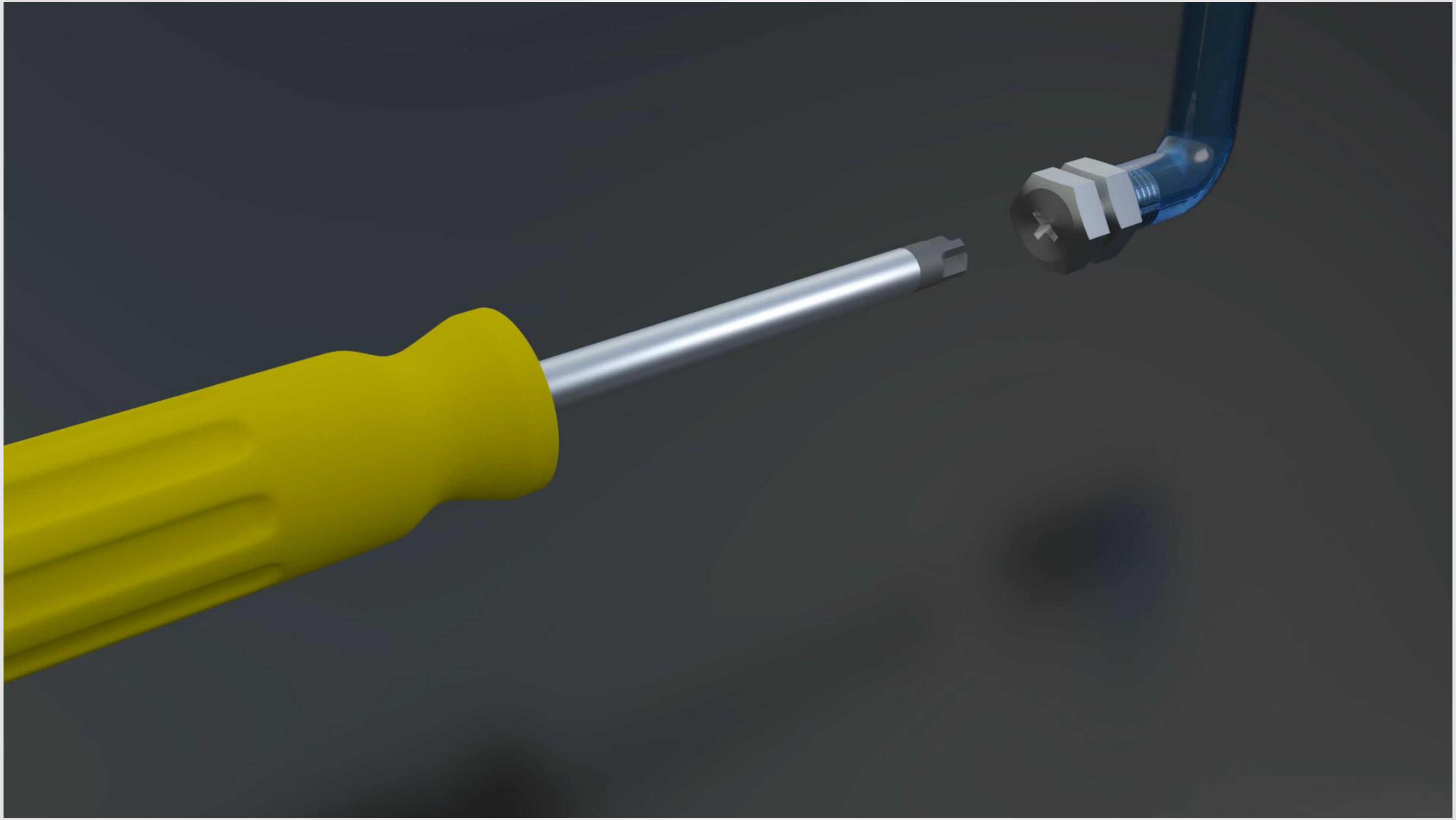
// Product development

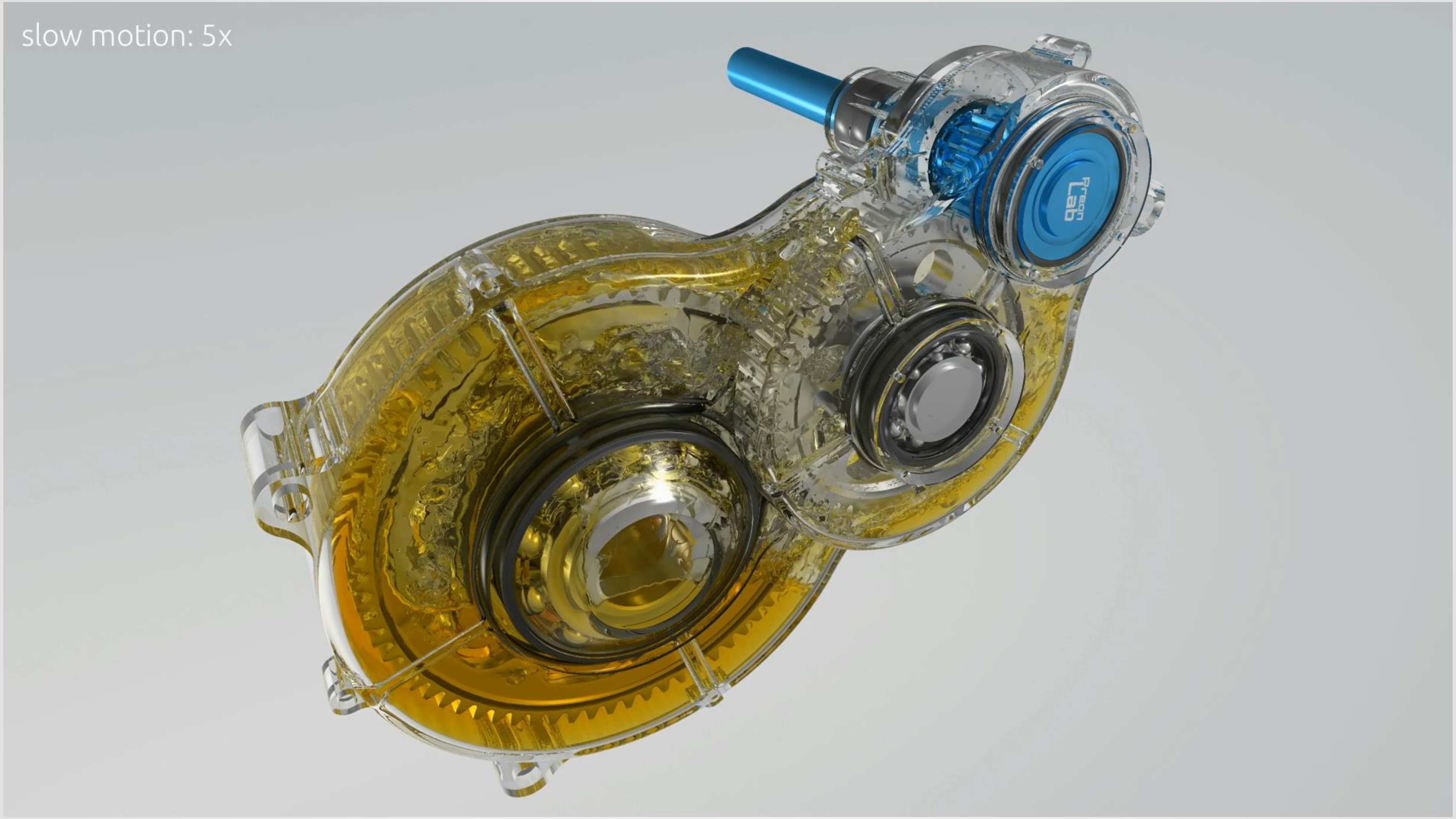
? Still a waste of time !

Include more physics:
- Improve quality
- New applications

Optimizations:
- Performance
- Workflow

// Particle-based rigid body solver




slow motion: 5x
Preon
Lab

// Highly viscous fluids