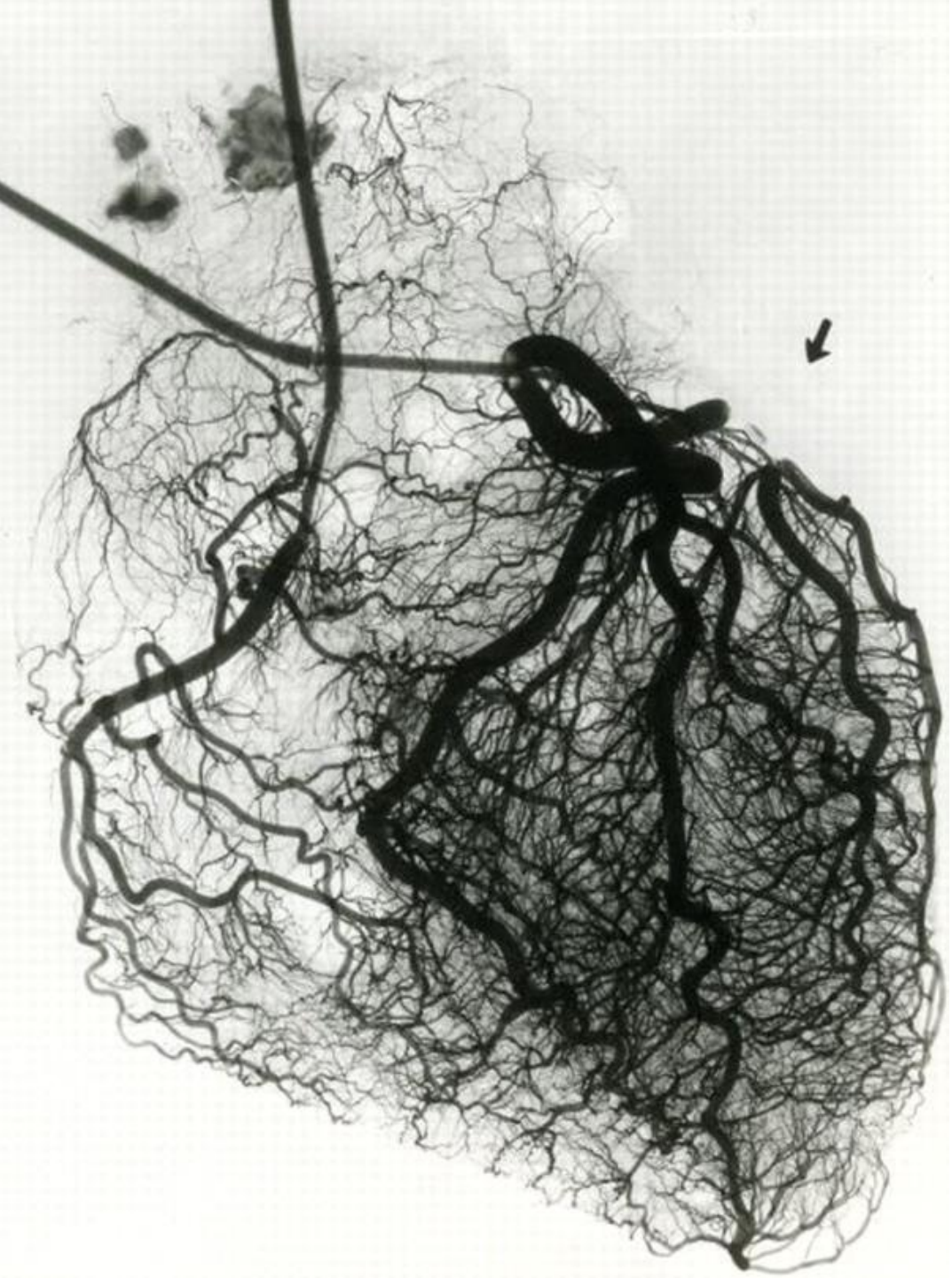
# Modelling and Simulation of Real Time Blood Flow in Vascular Networks

Mark Ian Holland

Supervisors

Serban Pop and Nigel John.



# Acute Cardiac Events

Myocardial Infarction:

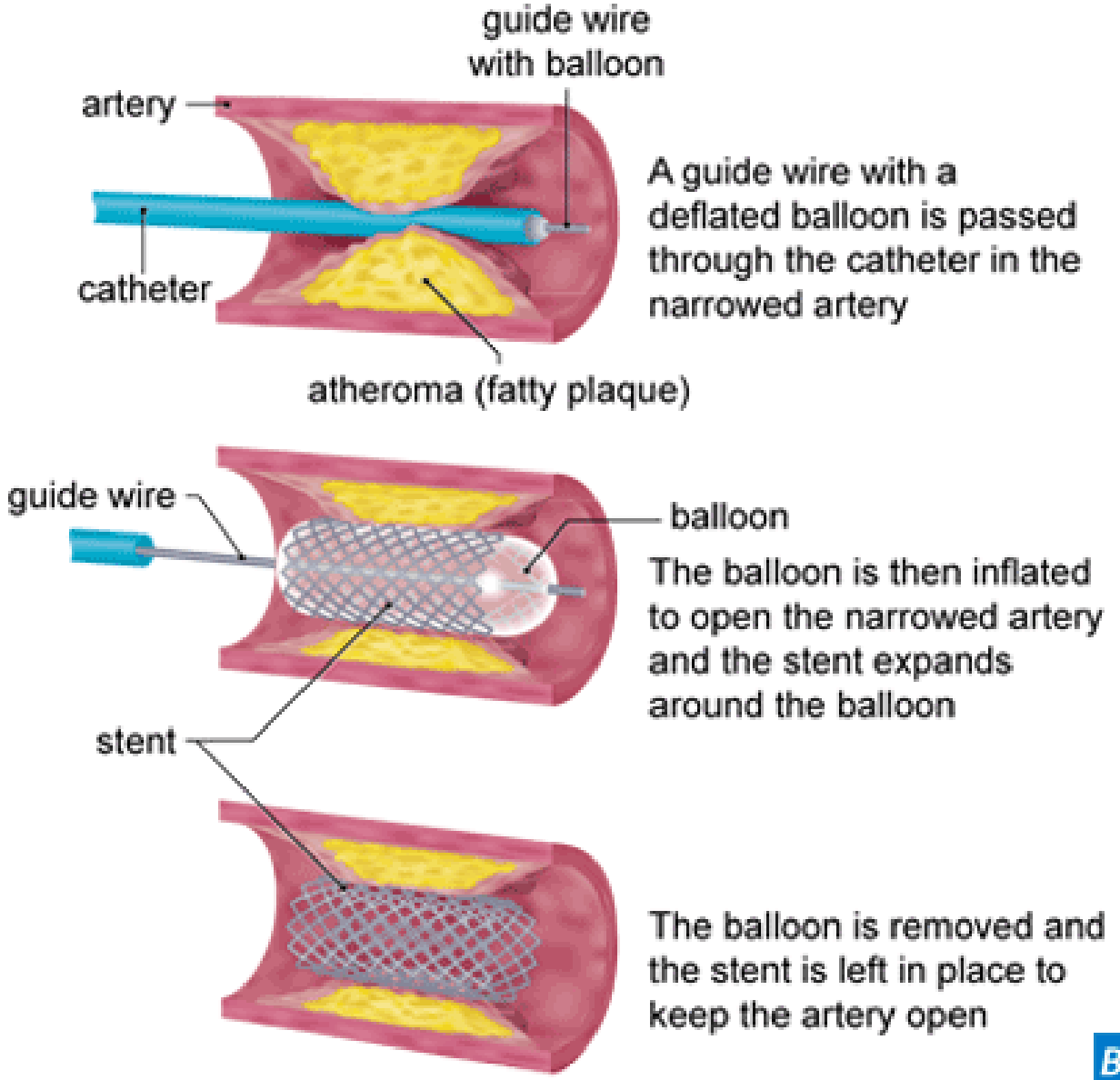
- The **blood supply** to a part of the heart is **interrupted**

Figure courtesy of European Heart Journal - eurheartj.oxfordjournals.org

# Treatment

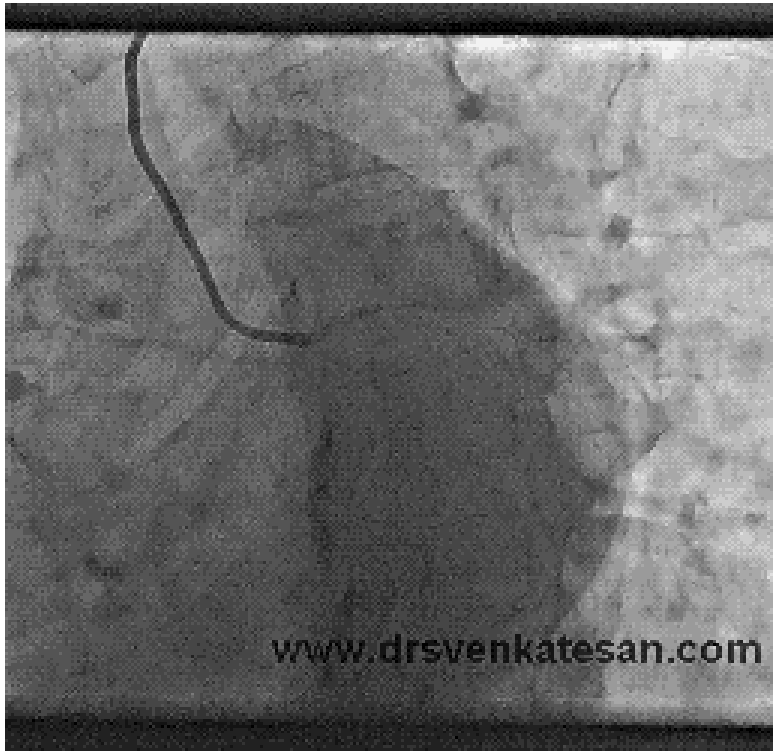
Coronary angioplasty:

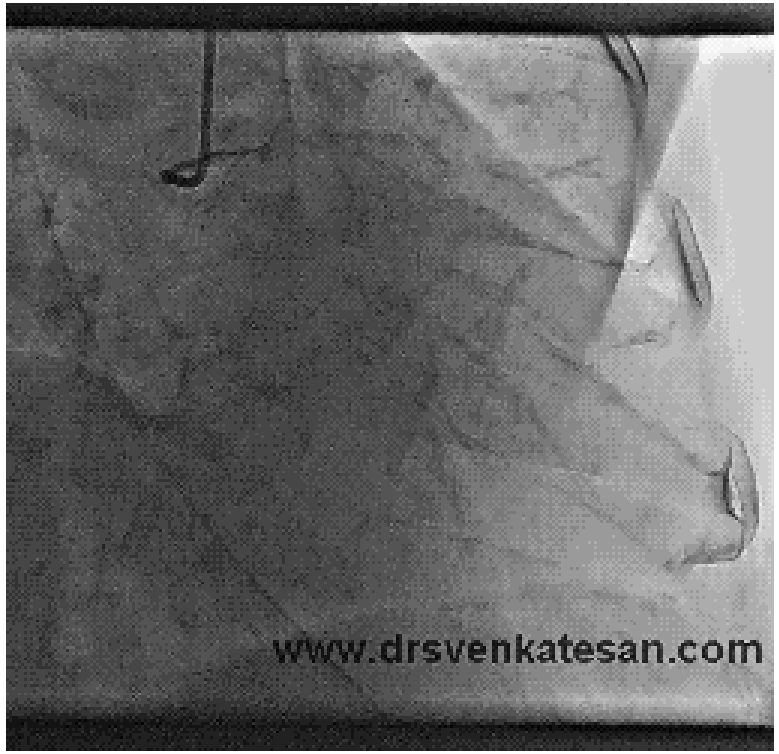
**Widen blocked or narrowed coronary arteries** (the main blood vessels supplying the heart).

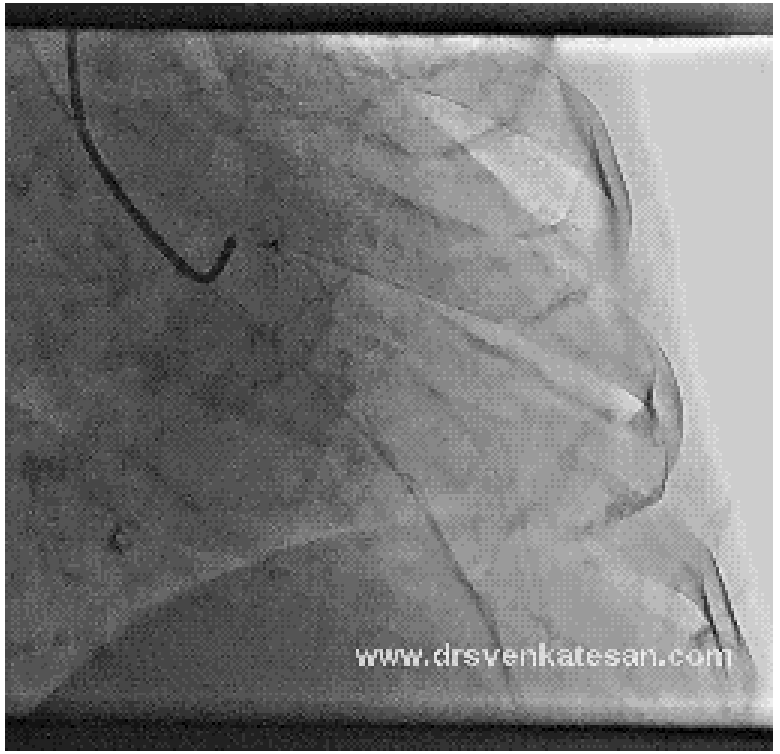



**A blood vessel treated with balloon angioplasty and stent**

# What Surgeons See



# What we can improve

- 3D
- Interactive
- Real-time

# Hypothesis

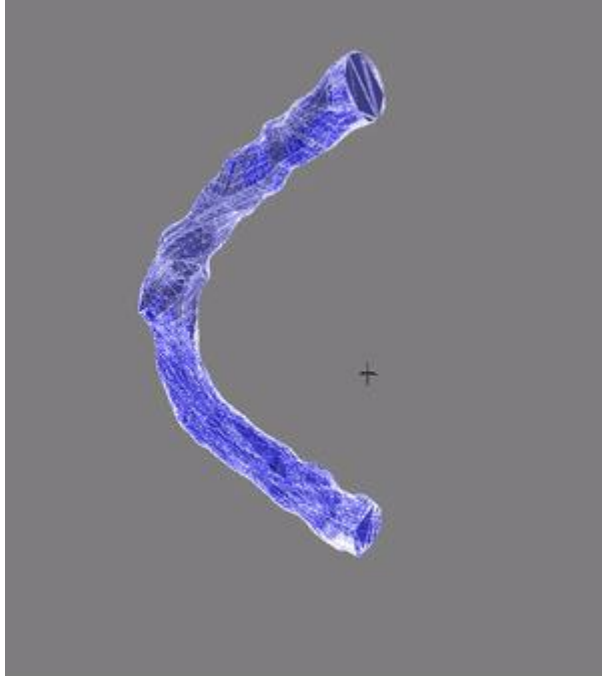
The interactive virtual reality blood flow simulator supports and enhances clinicians' decision and training process during major vascular events.

# 3D Visualisation

-OpenGL

-Viewing Experience

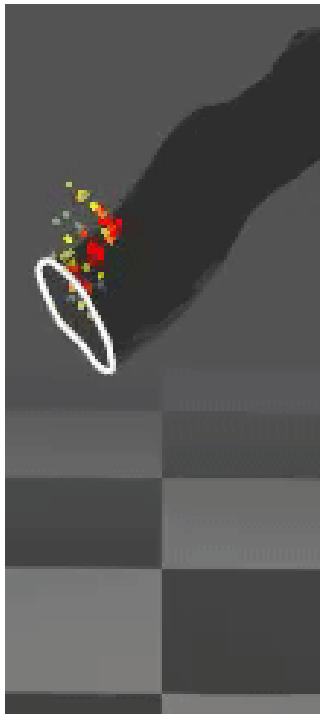
-Interactivity



zSpace®

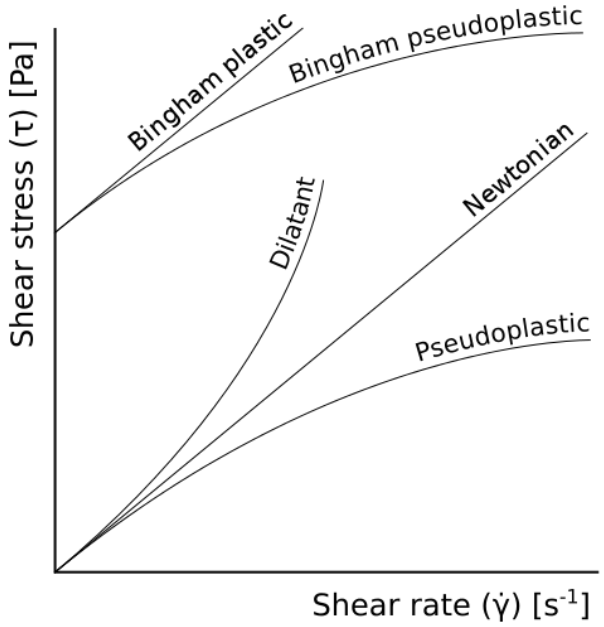
# Visual Continuity

- What is the minimum frequency frame rate to create an appropriate experience.
- Oculus Rift 90 frames per second
- zSpace 120Hz refresh rate
  - 60 FPS per eye



# Fluid Dynamics

- Moving Particles
- From Inlet to Outlet
- Boundary Condition
- Centreline

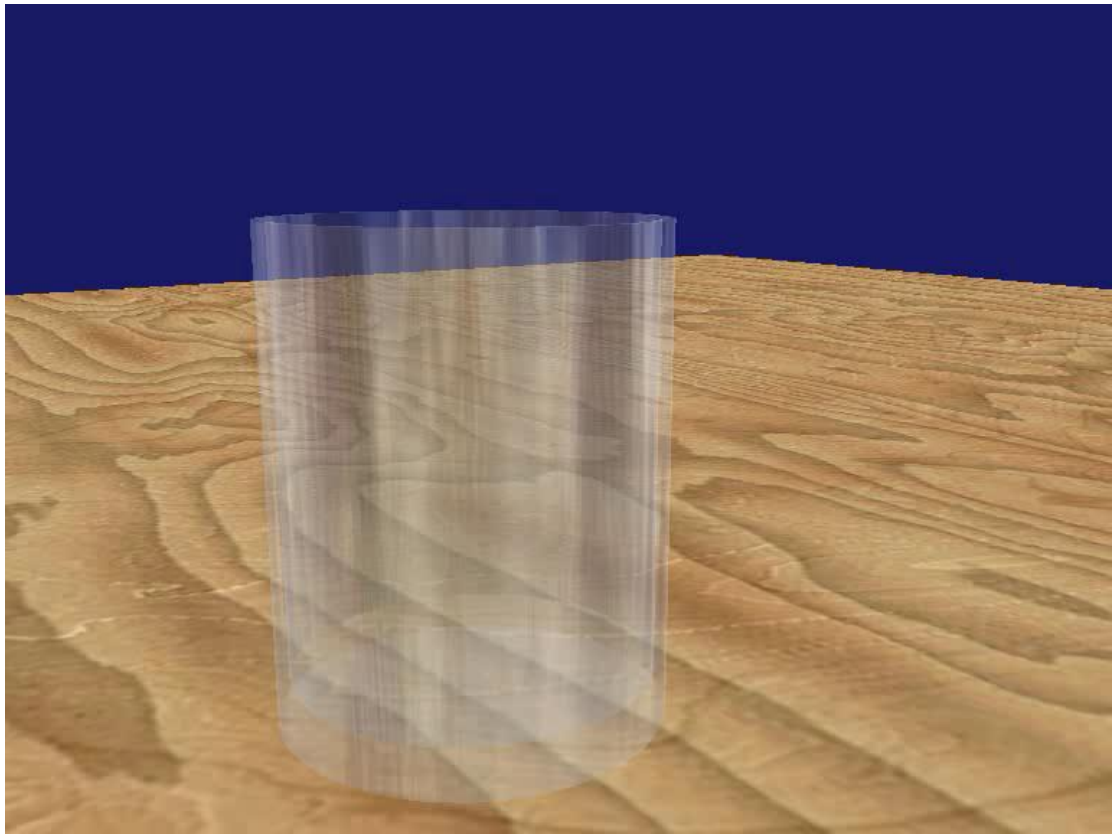



# Working With Blood

- Blood is a Non-Newtonian fluid.
- Newtonian fluids tend to conserve their physical flow properties (viscosity) regardless of any forces acting on it.
- Conservation of Mass

# Smoothed Particle Hydrodynamics (SPH)

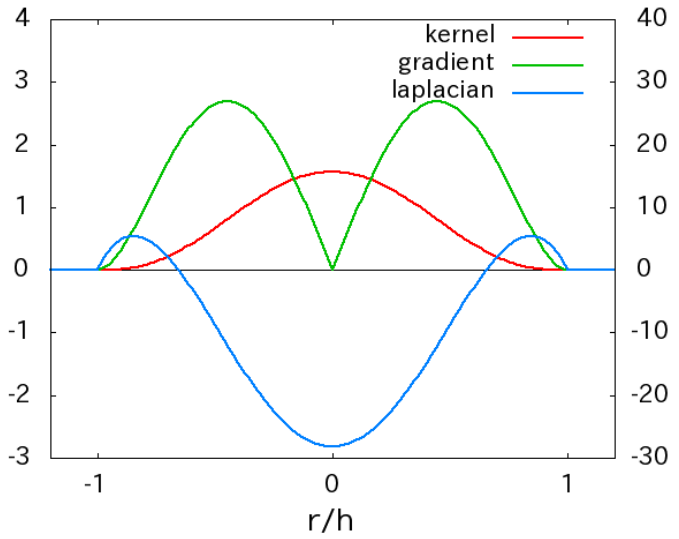
- Particle system
- Highly **accurate**
- Time consuming



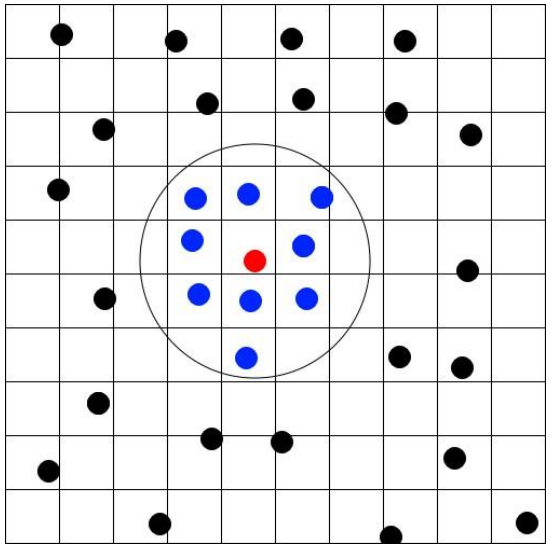
*Müller, M., Charypar, D., & Gross, M. (2003, July). Particle-based fluid simulation for interactive applications. In Proceedings of the 2003 ACM SIGGRAPH/Eurographics symposium on Computer animation (pp. 154-159). Eurographics Association.*

# Smoothed Particle Hydrodynamics (SPH)

- Nearest Neighbour
- Smoothing Kernels
  - Stability, accuracy and speed of the SPH method highly depend on the choice of the smoothing kernels (Muller 2003).




http://www.slis.tsukuba.ac.jp/

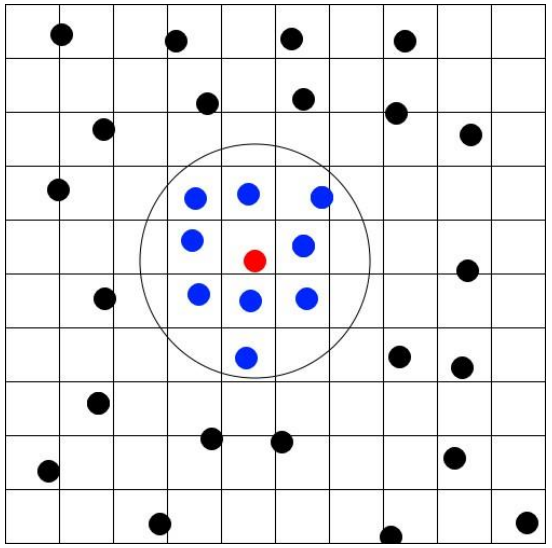


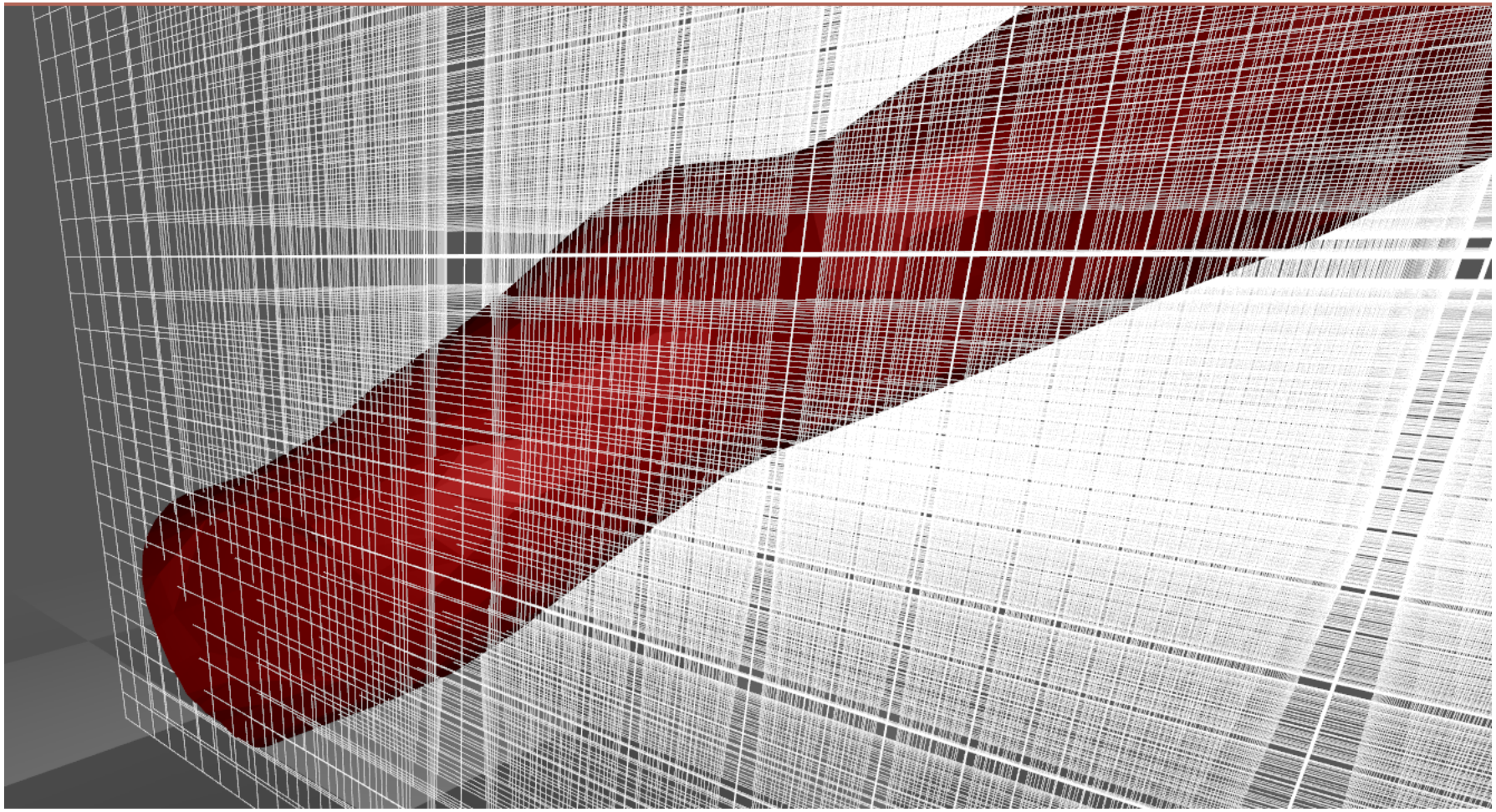
*Weaver, T., & Xiao, Z. (2016)*

*Weaver, T., & Xiao, Z. (2016). Fluid Simulation by the Smoothed Particle Hydrodynamics Method: A Survey.*
*Müller, M., Charypar, D., & Gross, M. (2003, July). Particle-based fluid simulation for interactive applications. In Proceedings of the 2003 ACM SIGGRAPH/Eurographics symposium on Computer animation (pp. 154-159). Eurographics Association.*

$$A_S(\mathbf{r}) = \sum_j m_j \frac{A_j}{\rho_j} W(\mathbf{r} - \mathbf{r}_j, h)$$

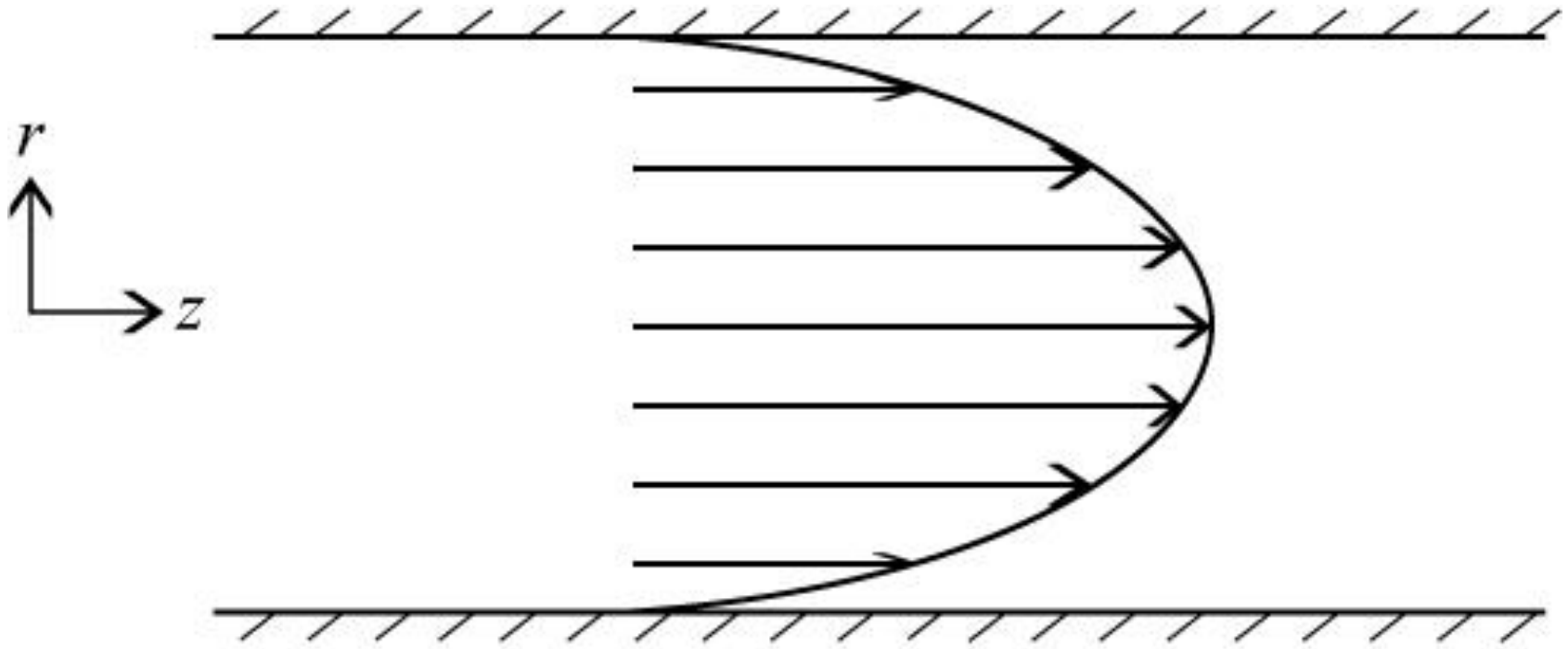
# Nearest Neighbour Searching & Spatial Hashing





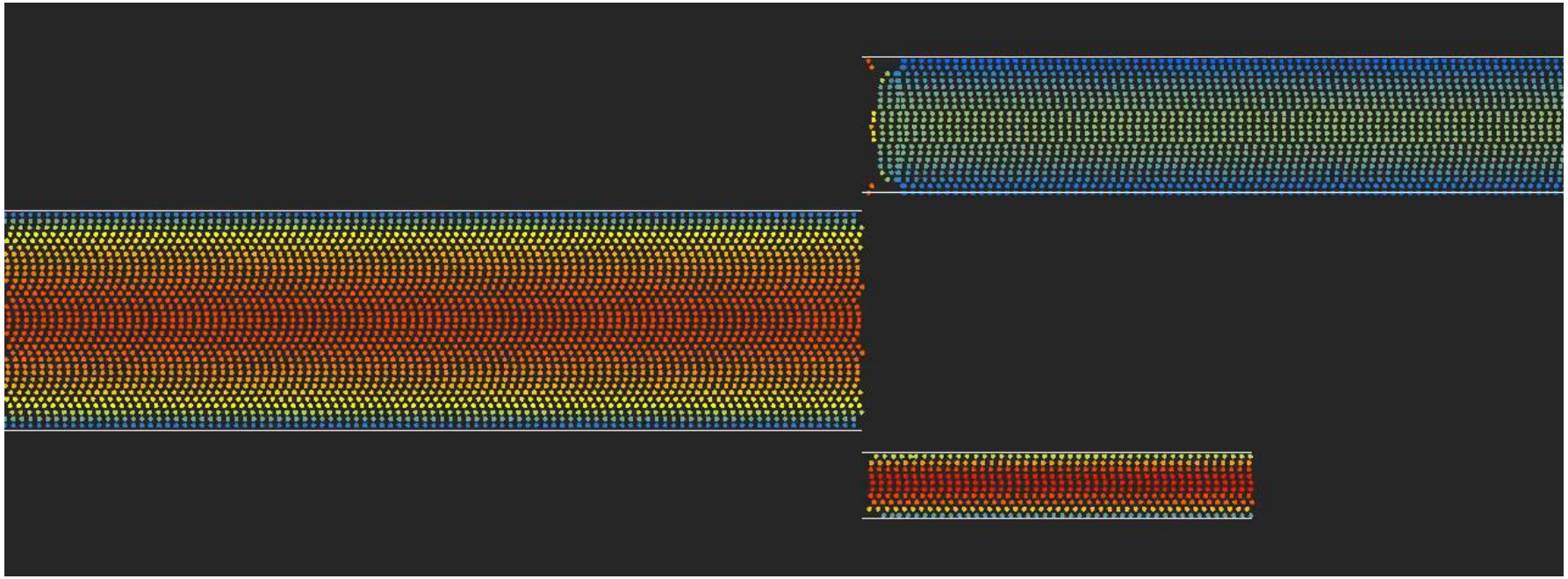
# Fluid In Tubes

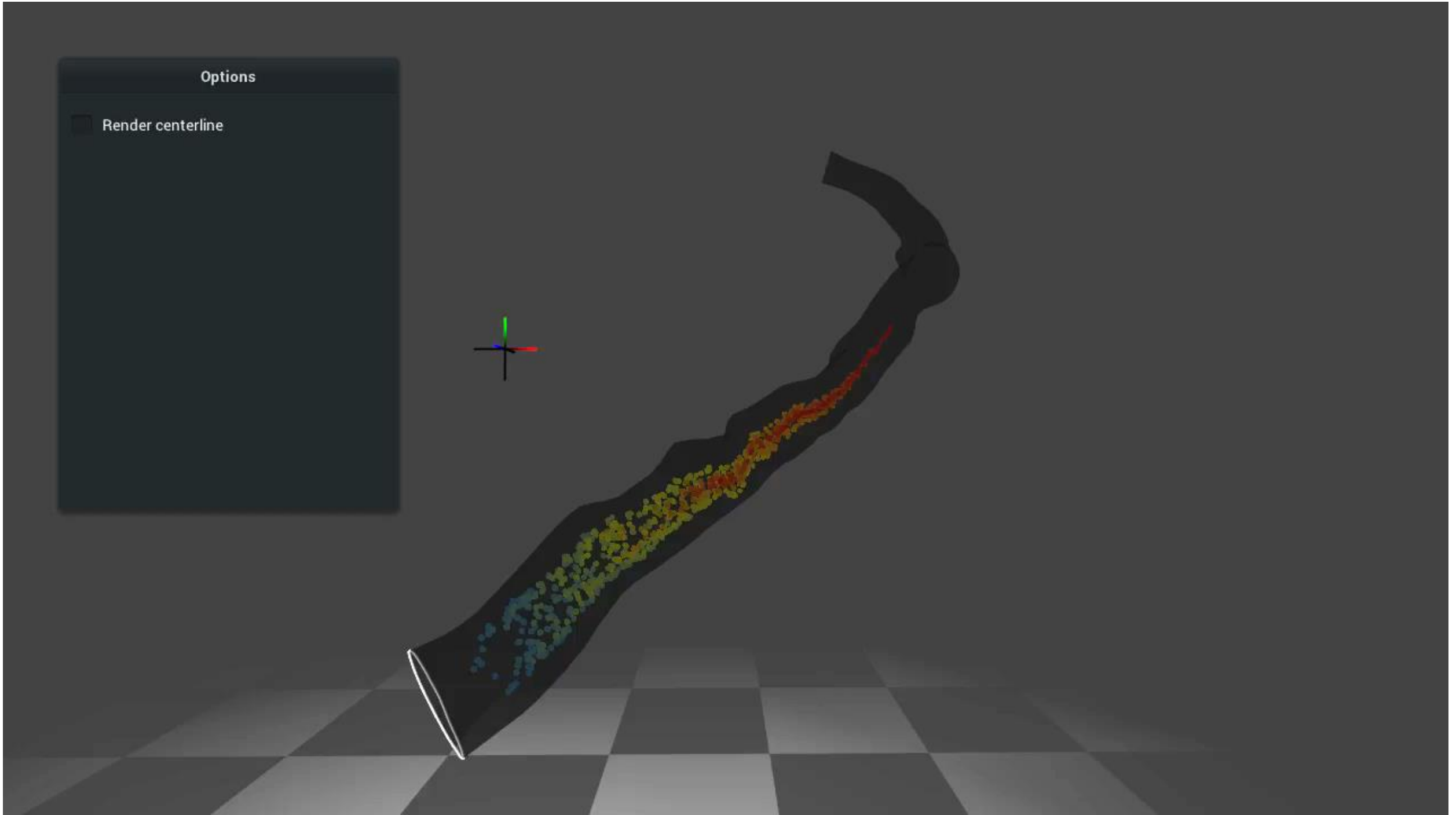
Poiseuille flow



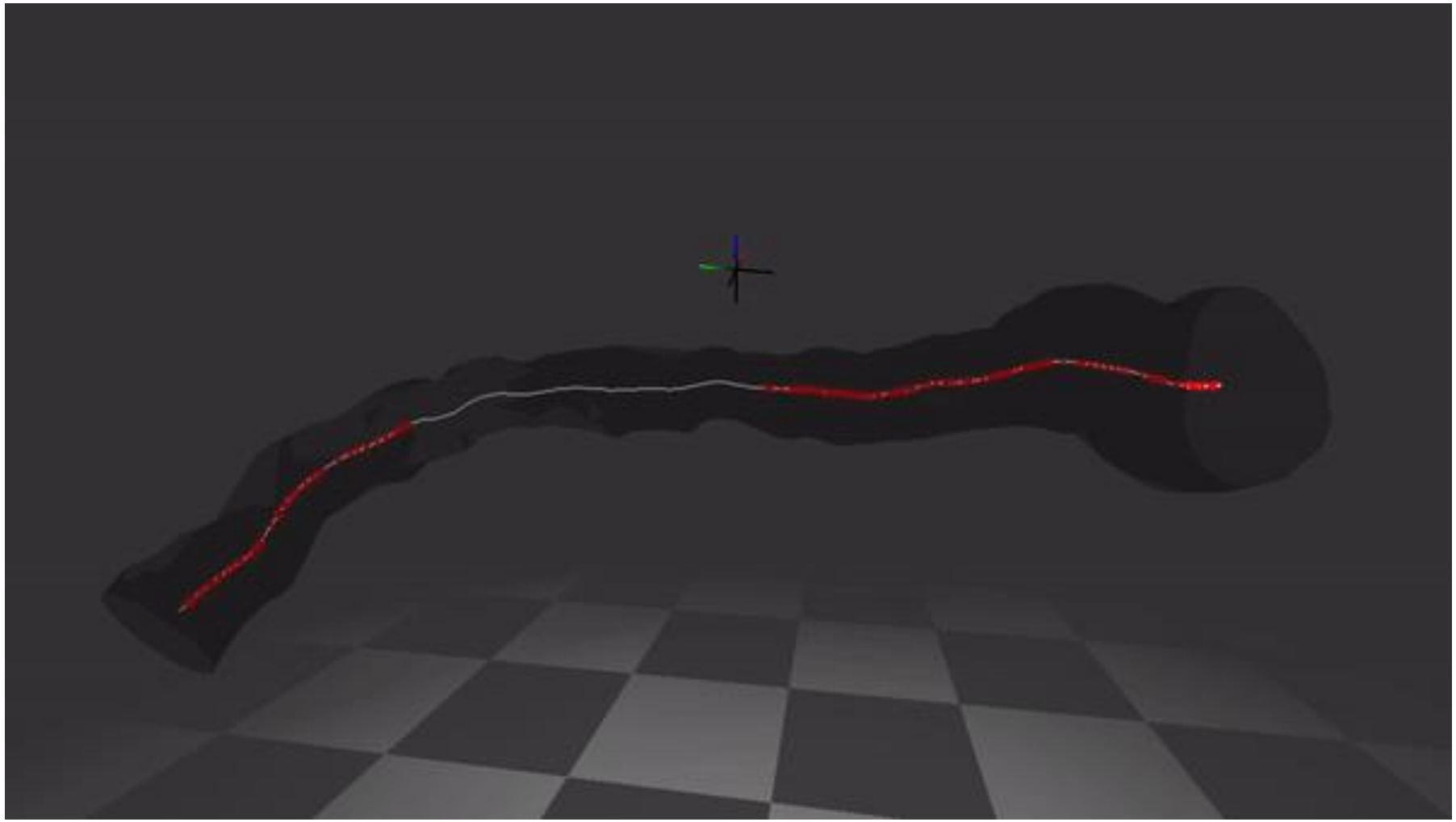
# Fluid In Tubes

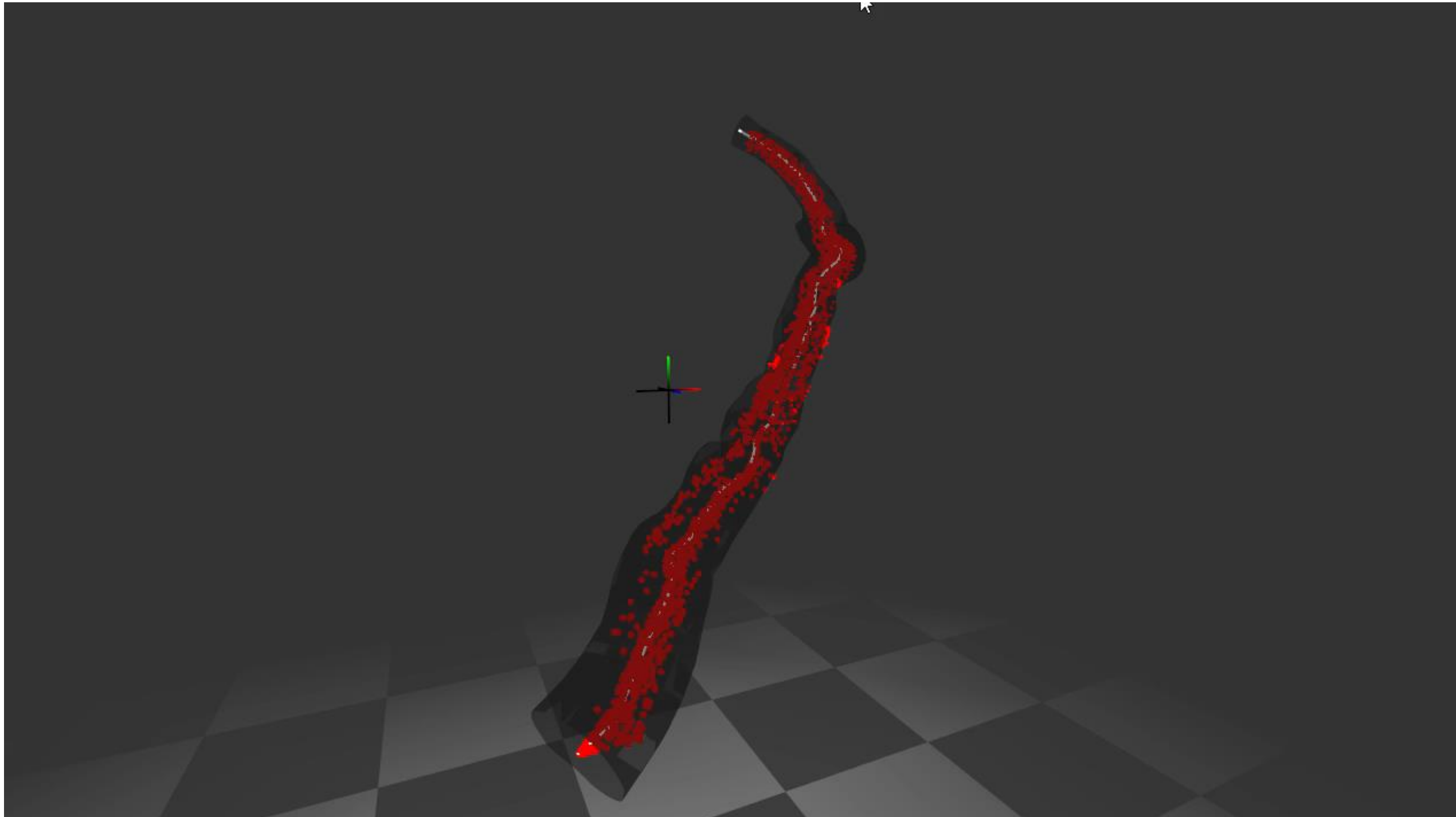
Poiseuille flow




Options
Render centerline

# Centreline





# Patient Geometry

-Mesh

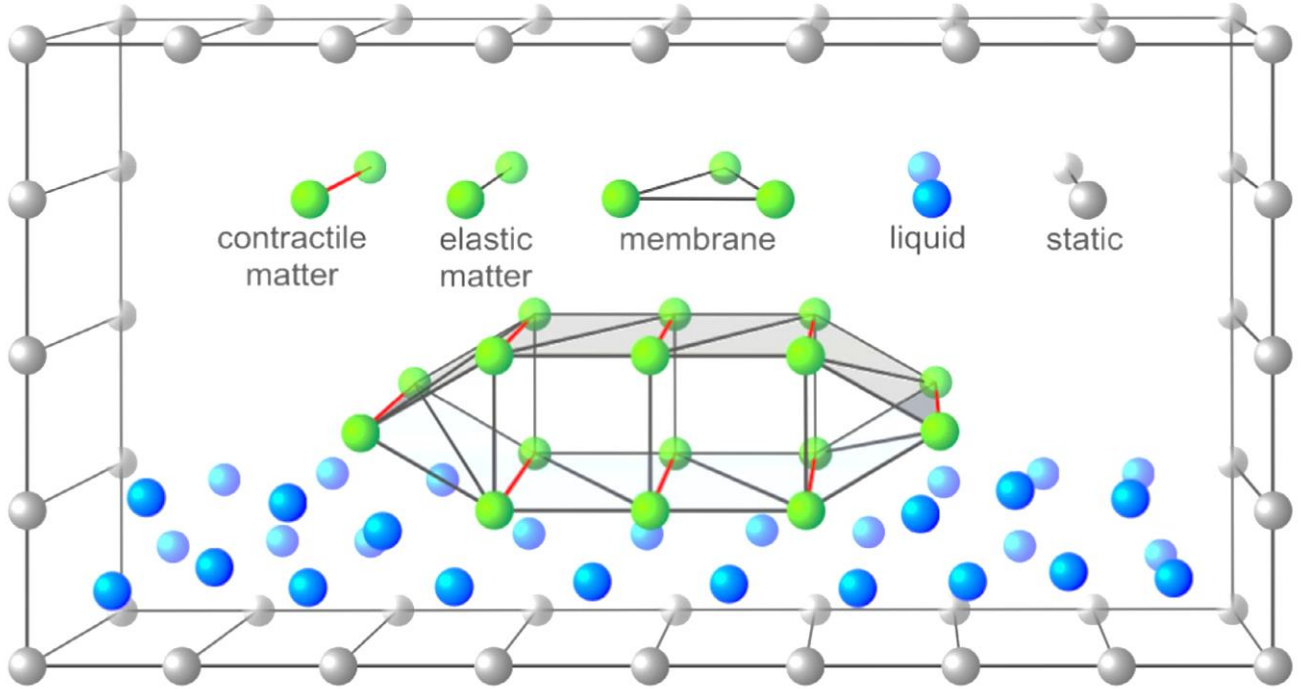
-Integrate Artery

-Changes In the domain

# Boundary Conditions

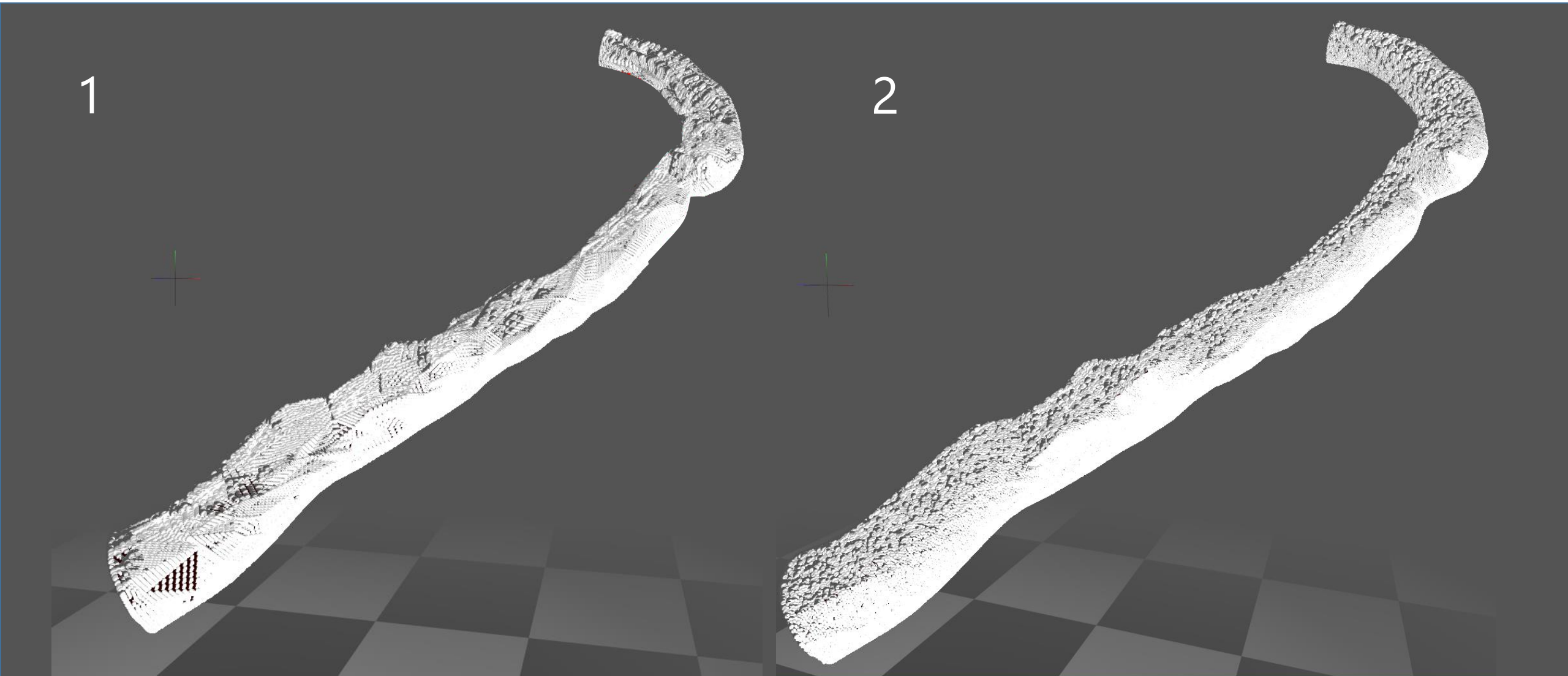
Particle Representation

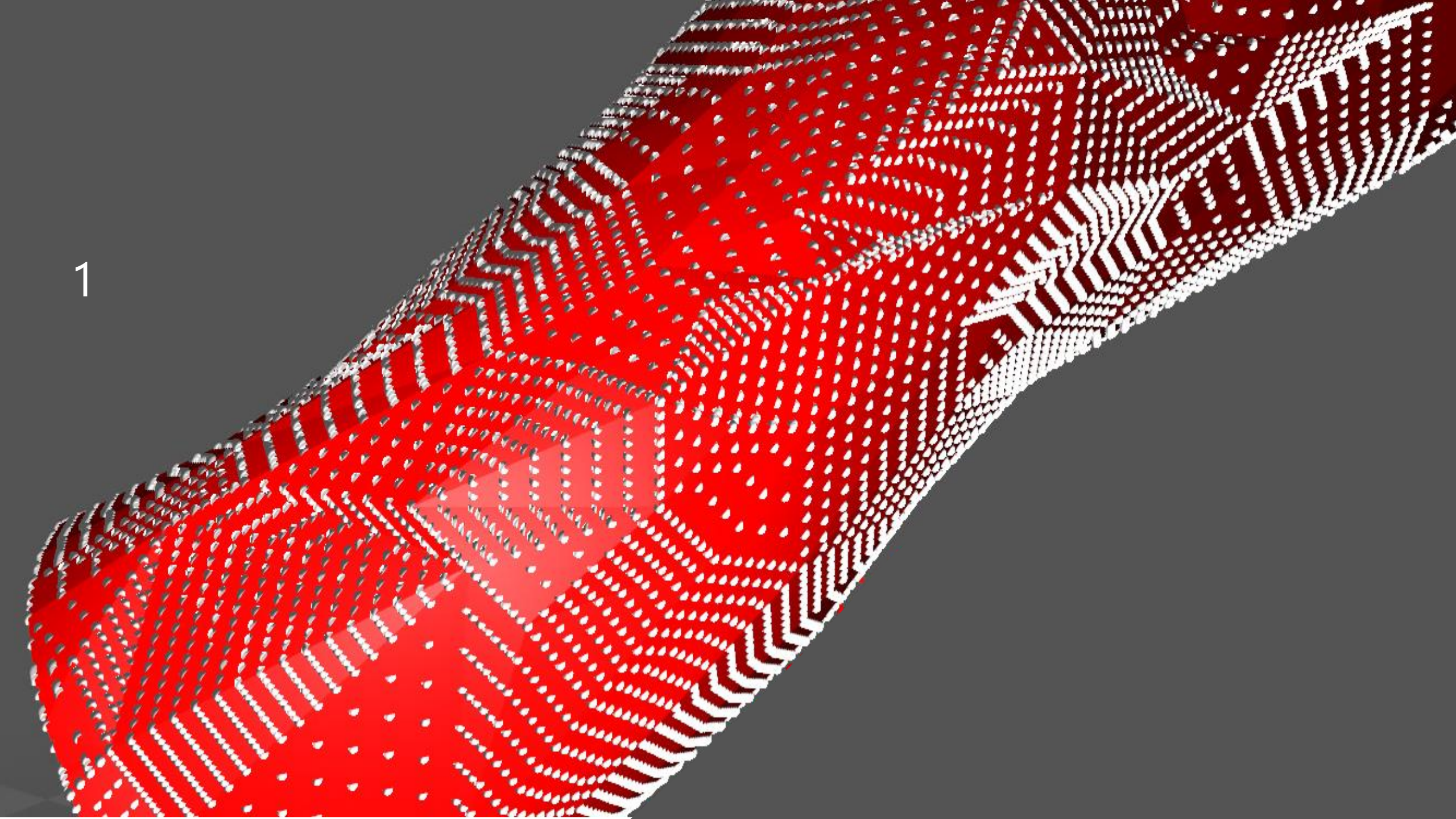
Interaction between blood and the vessel walls

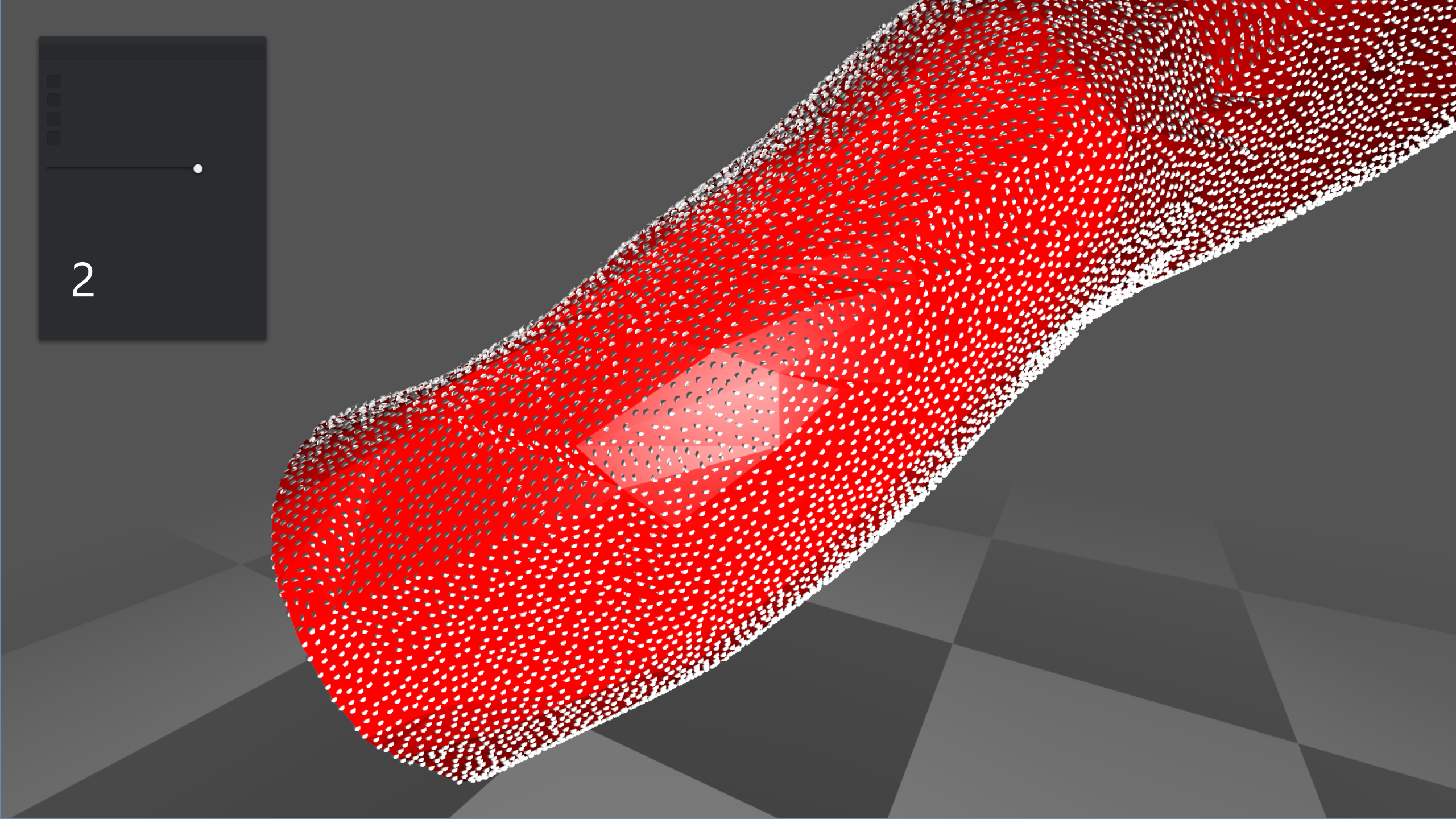



Palyanov, A., Khayrulin, S., & Larson, S. D. (2016). Application of smoothed particle hydrodynamics to modeling mechanisms of biological tissue.*Advances in Engineering Software*, *98*, 1-11.

# Sampling




1

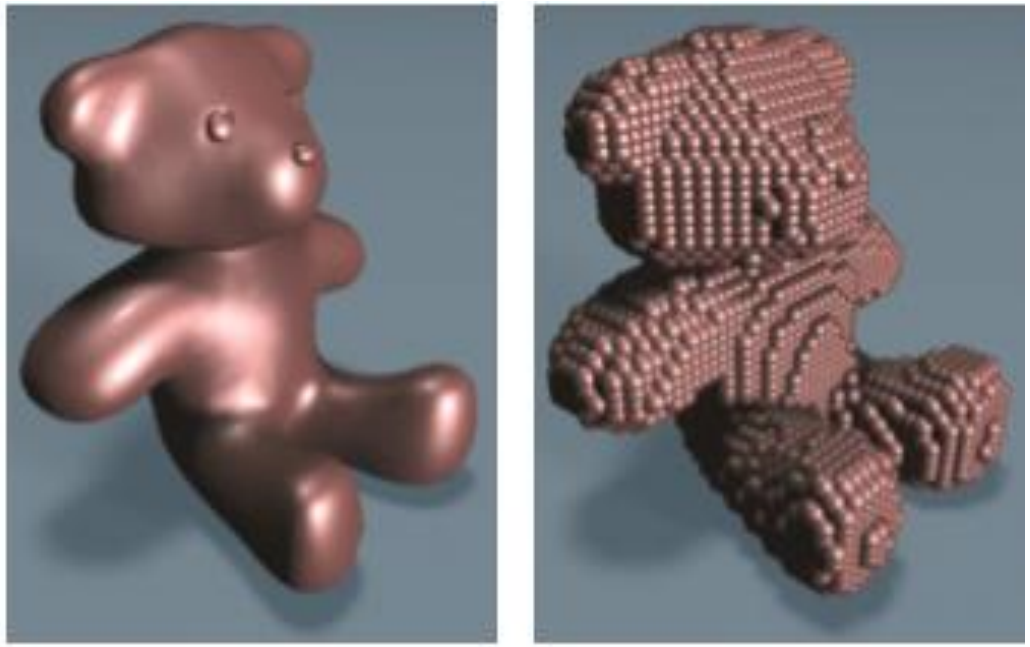

2


FPS: 56.40
Particle Count: 424
Options
Render centerline
Highlight inlet
Render bounding box
Draw Grid
Vessel Alpha

# Rigid Bodies

In the context of rigid-fluid coupling, various rigid-body representations have been proposed:

- triangle meshes,
- adaptively sampled distance fields
- particles.



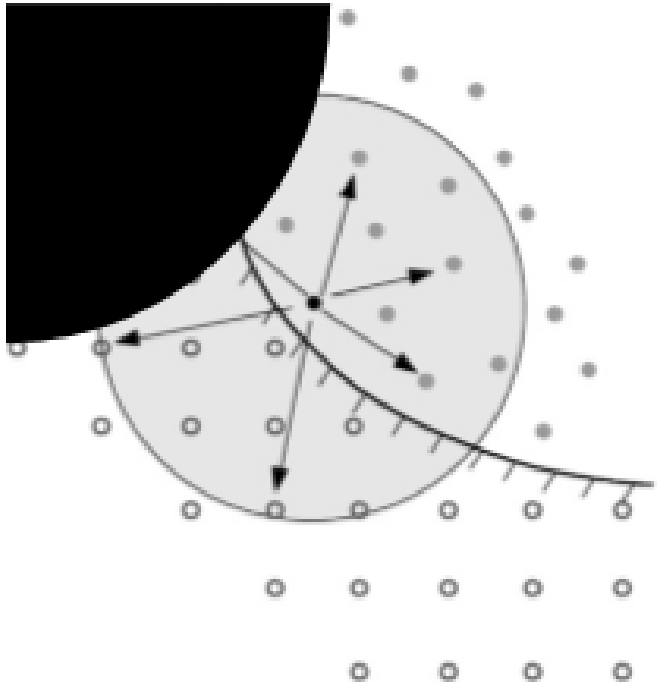
Triangulated surface and particle representation of a teddy model.

The particle representation is generated in a pre-processing step using a distance field.

Becker, M., Tessendorf, H., & Teschner, M. (2009). Direct forcing for lagrangian rigid-fluid coupling. *IEEE Transactions on Visualization and Computer Graphics*, *15*(3), 493-503.

# Boundary Conditions Continued

- Mirror Particles
- Ghost Particles
- Kernel Correction



Adami, S., Hu, X. Y., & Adams, N. A. (2012).

*Adami, S., Hu, X. Y., & Adams, N. A. (2012). A generalized wall boundary condition for smoothed particle hydrodynamics. Journal of Computational Physics, 231(21), 7057-7075.*

*Allahdadi, F. A., Carney, T. C., Hipp, J. R., Libersky, L. D., & Petschek, A. G. (1993). High strain Lagrangian hydrodynamics: a three dimensional SPH code for dynamic material response (No. PL-TR-92-1054). Phillips Lab Kirtland AFB NM.*

Bender, J., Erleben, K., & Teschner, M. (2010). Boundary handling and adaptive time-stepping for PCISPH. In *Workshop on virtual reality interaction and physical simulation VRIPHYS*

# Challenges

- Particles Escaping
  - Sub Steps
  - Density Correction
- Accurate Boundary Condition
- **Interaction**
- **Performance**

# Validation

- Numerical fluid simulations are validated by comparison to other data sets and other forms of benchmarking.
- Comparison with documented phenomena
- Acceptable performance prevent suitable validation. Muller (2004) found the number of particles was significantly too low to compare to measured data.

*Müller, M., Schirm, S., & Teschner, M. (2004). Interactive blood simulation for virtual surgery based on smoothed particle hydrodynamics. Technology and Health Care, 12(1), 25-31.*

*Adami, S., Hu, X. Y., & Adams, N. A. (2012). A generalized wall boundary condition for smoothed particle hydrodynamics. Journal of Computational Physics, 231(21), 7057-7075.*

*Allahdadi, F. A., Carney, T. C., Hipp, J. R., Libersky, L. D., & Petschek, A. G. (1993). High strain Lagrangian hydrodynamics: a three dimensional SPH code for dynamic material response (No. PL-TR-92-1054). Phillips Lab Kirtland AFB NM.*

Becker, M., Tessendorf, H., & Teschner, M. (2009). Direct forcing for lagrangian rigid-fluid coupling. *IEEE Transactions on Visualization and Computer Graphics*, *15*(3), 493-503.

Bender, J., Erleben, K., & Teschner, M. (2010). Boundary handling and adaptive time-stepping for PCISPH. In *Workshop on virtual reality interaction and physical simulation VRIPHYS*.

*Müller, M., Charypar, D., & Gross, M. (2003, July). Particle-based fluid simulation for interactive applications. In Proceedings of the 2003 ACM SIGGRAPH/Eurographics symposium on Computer animation (pp. 154-159). Eurographics Association.*

*Müller, M., Schirm, S., & Teschner, M. (2004). Interactive blood simulation for virtual surgery based on smoothed particle hydrodynamics. Technology and Health Care, 12(1), 25-31.*

Palyanov, A., Khayrulin, S., & Larson, S. D. (2016). Application of smoothed particle hydrodynamics to modeling mechanisms of biological tissue.*Advances in Engineering Software*, *98*, 1-11.
*Weaver, T., & Xiao, Z. (2016). Fluid Simulation by the Smoothed Particle Hydrodynamics Method: A Survey.*