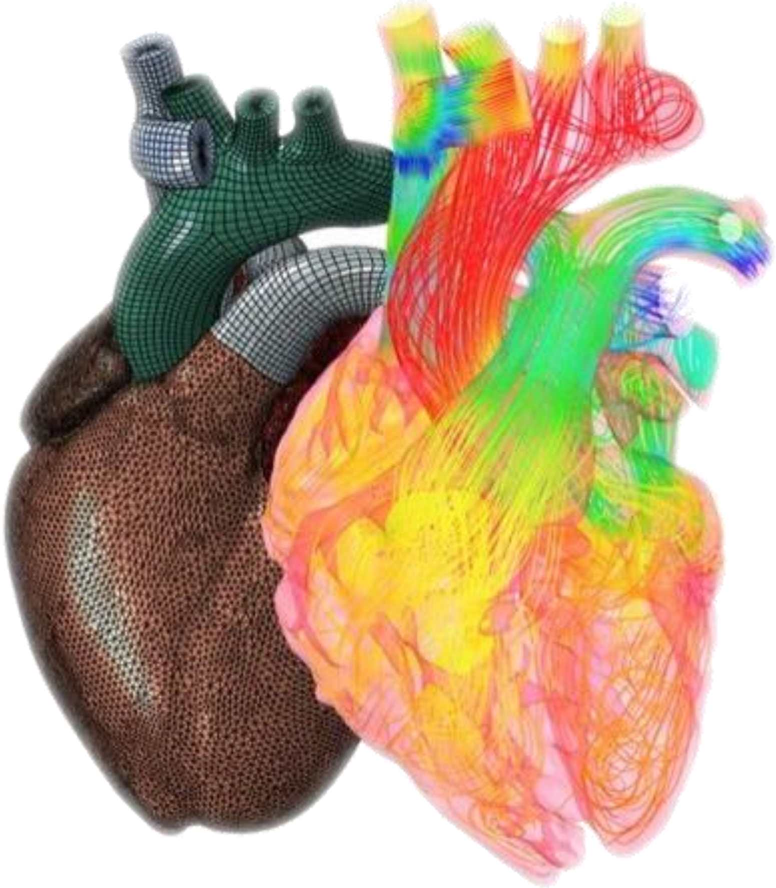
Understanding Cardiovascular Disease with Computer Simulations

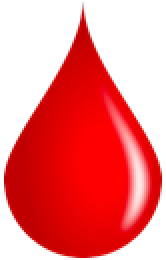


National Biomechanics Day at CMU

Our plan for today

Fluid mechanics → Computational fluid dynamics (CFD) → CFD and cardiovascular diseases → Tutorial

What is a fluid?

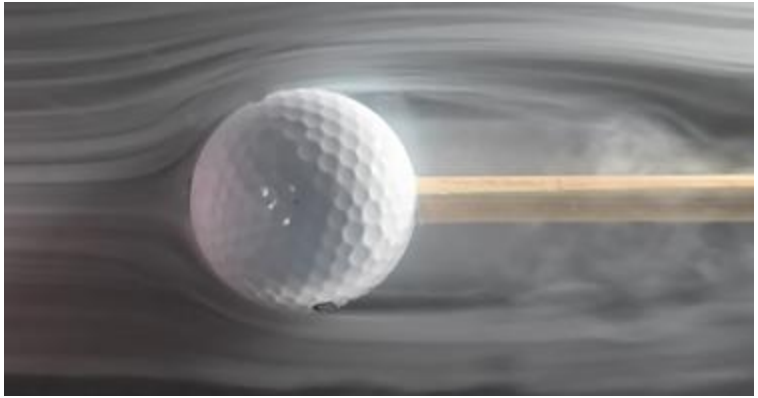


Fluid:

A material that continuously deforms under applied shear stress

Fluid mechanics is the study of fluids in…

motion (*fluid dynamics*)



at rest (*fluid statics*)

Why do we study fluid dynamics?

1. Understand fluid flow (velocity, pressure)

2. Understand how influences objects (forces, energy)

Why do we care about fluids in our body?

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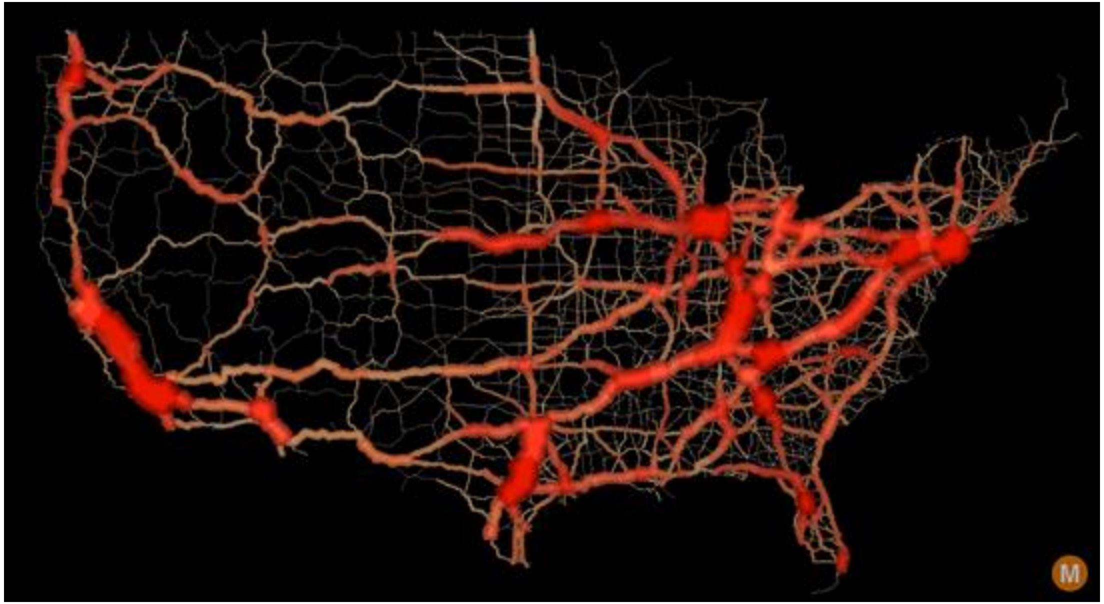


We use the ***Navier-Stokes Equations**** to describe the behavior of any fluid

$$\nabla \cdot \overline{u} = 0$$

$$\rho \frac{D\overline{u}}{Dt} = -\nabla p + \mu \nabla^2 \overline{u} + \rho \overline{F}$$

But… these equations are very difficult to solve for complex problems!

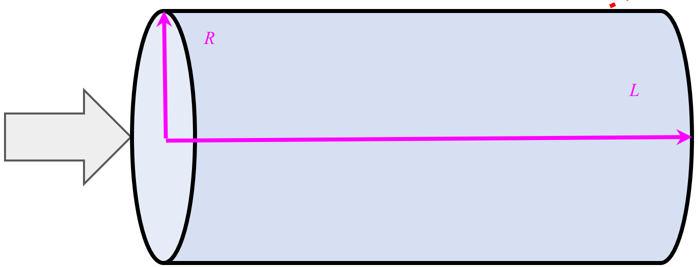
*One of the seven Millennium Prize Problems:
https://www.claymath.org/millennium-problems/navier–stokes-equation

However, we can solve these equations for some simple problems!

Simple example 1: Poiseuille flow

Simple example 1: Poiseuille flow

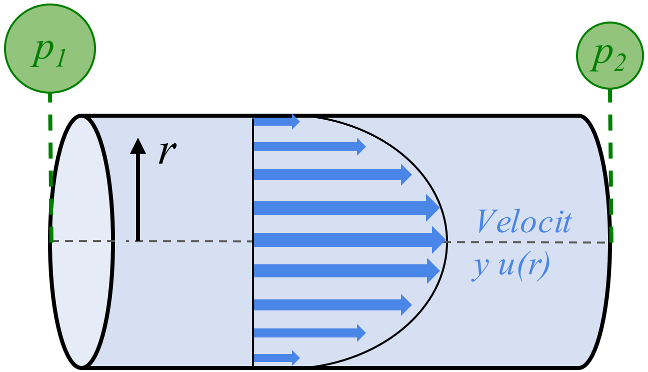
Q: Flow rate [ml/s]



What does the velocity change throughout the pipe

How much pressure do we need to push this water?

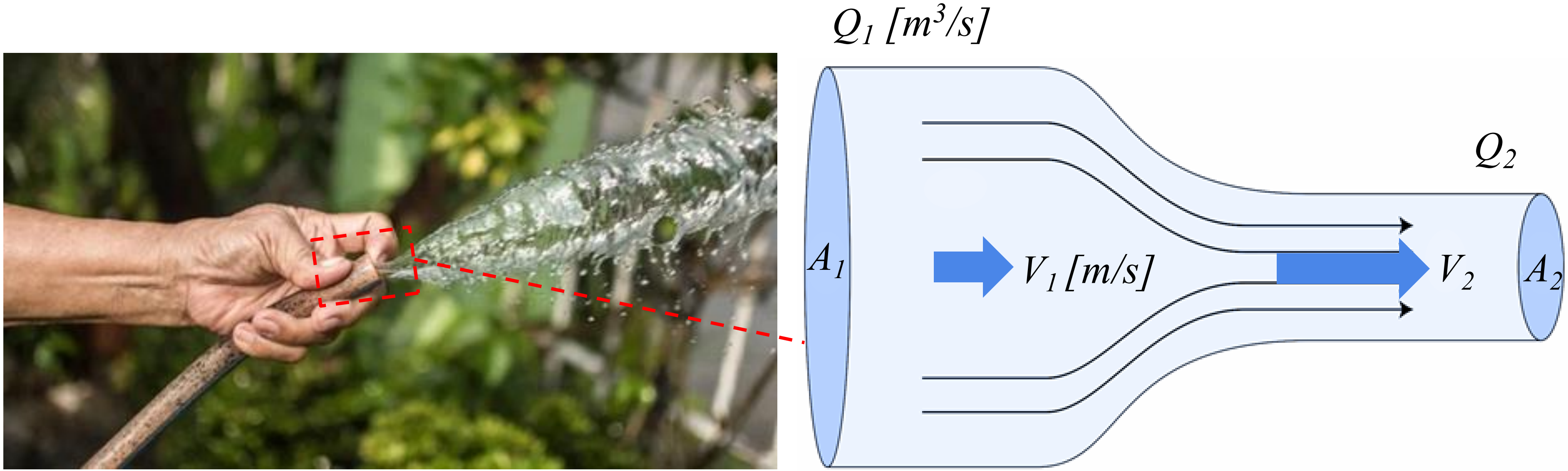
Using Navier-Stokes, we can predict that…



$$P_1 - P_2 = \Delta P = \frac{8\mu LQ}{\pi R^4} \quad [Pa]$$

$$u = \frac{2Q}{\pi R^2}(R^2 - r) \quad [m/s]$$

Simple example 2: Mass conservation

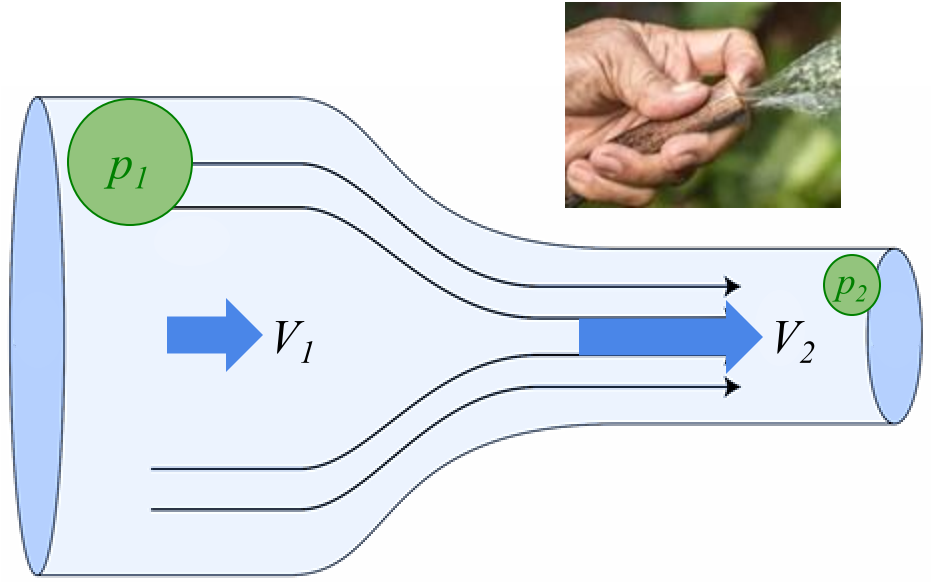


$$Q_1 = Q_2$$

$$A_1 V_1 = A_2 V_2$$

The flow rate does not change, but velocity does!

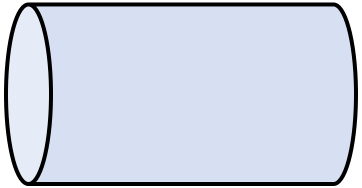
Simple example 3: Bernoulli’s Principle

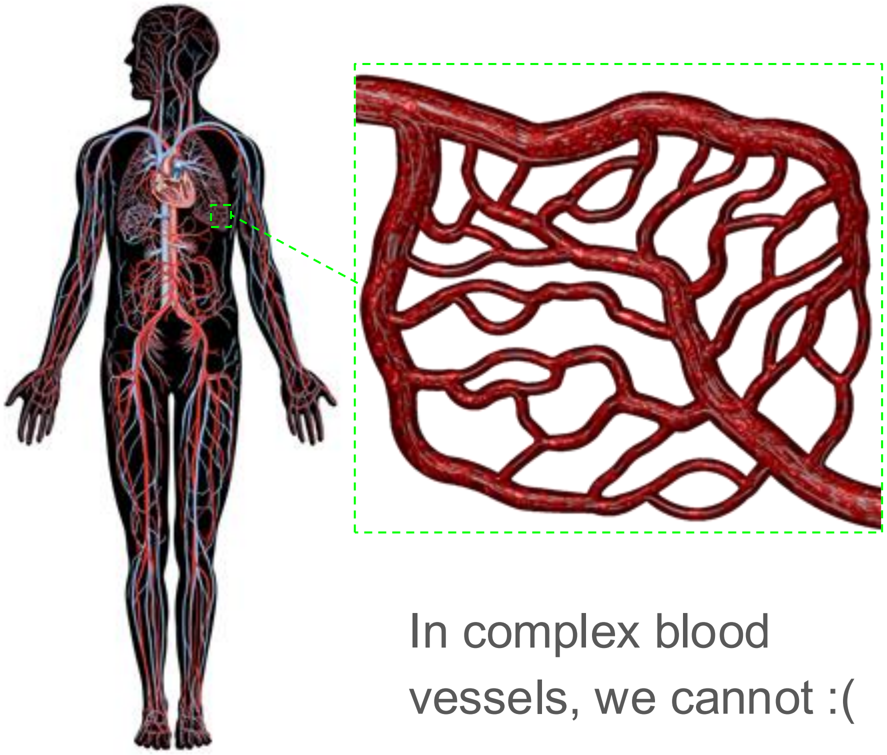


$$\overbrace{P_1 + \frac{\rho}{2} V_1^2}^{\text{Region 1}} = \overbrace{P_1 + \frac{\rho}{2} V_2^2}^{\text{Region 2}}$$

Bernoulli’s Principle tells us how *energy* (velocity, pressure) *changes throughout* the fluid

Going from simple fluid dynamics problems to complex ones

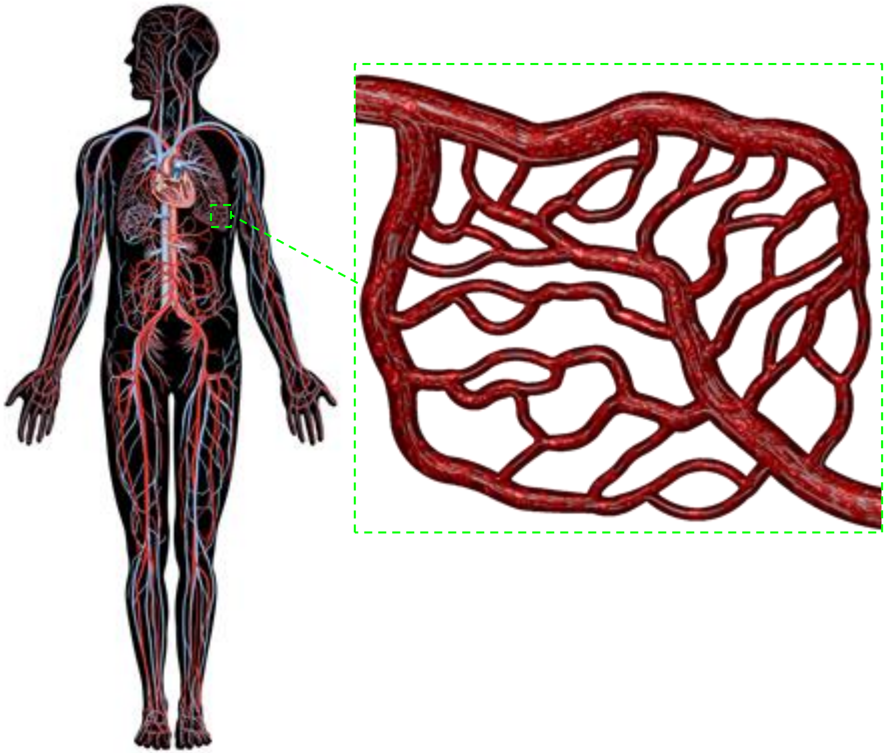




In a straight pipe, we can find a simple equation!

In complex blood vessels, we cannot :(

What do we do for complex problems, like the human body?



We have to solve these equations with *computational fluid dynamics*!

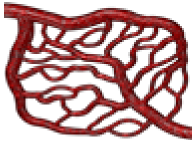
$$\nabla \cdot \overline{u} = 0$$

$$\rho \frac{D\overline{u}}{Dt} = -\nabla p + \mu \nabla^2 \overline{u} + \rho \overline{F}$$

What are Computational Fluid Dynamics (CFD) models?

What? Solve fluid dynamics equations using **computer models**.

1 Real world

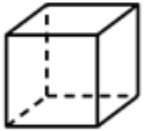


2 Mathematical model

$$\nabla \cdot \overline{u} = 0$$

$$\rho \frac{D\overline{u}}{Dt} = -\nabla p + \mu \nabla^2 \overline{u} + \rho \overline{F}$$

3 Computational Mesh



Hexahedron

Tetrahedron

4 Simulation

Computer Model

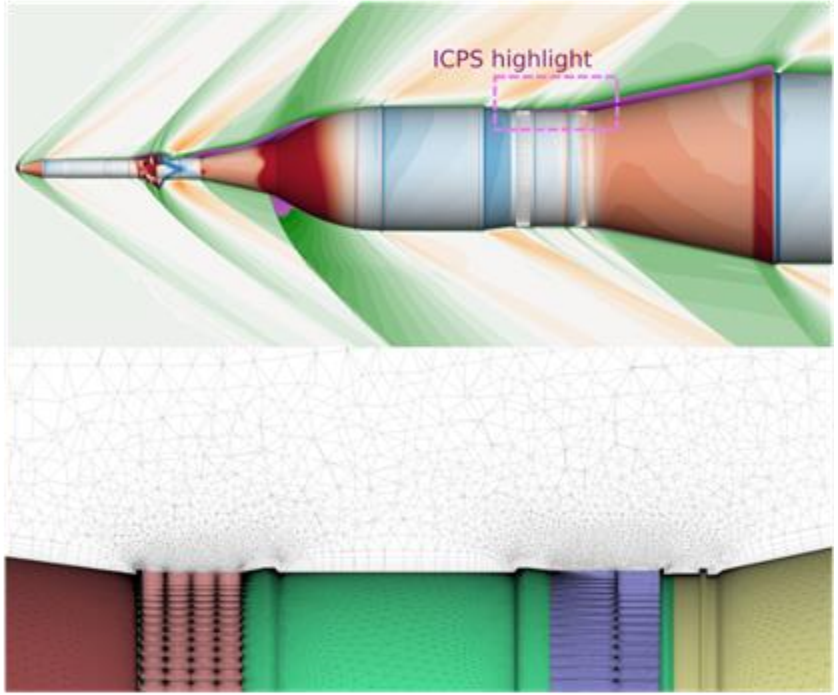
Not your regular computer!

=

~ 3000 laptops!!

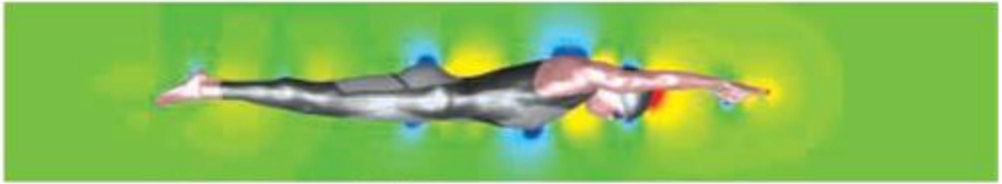
Pittsburgh Supercomputing Center (PSC)

Aerospace aerodynamics



Source: NASA

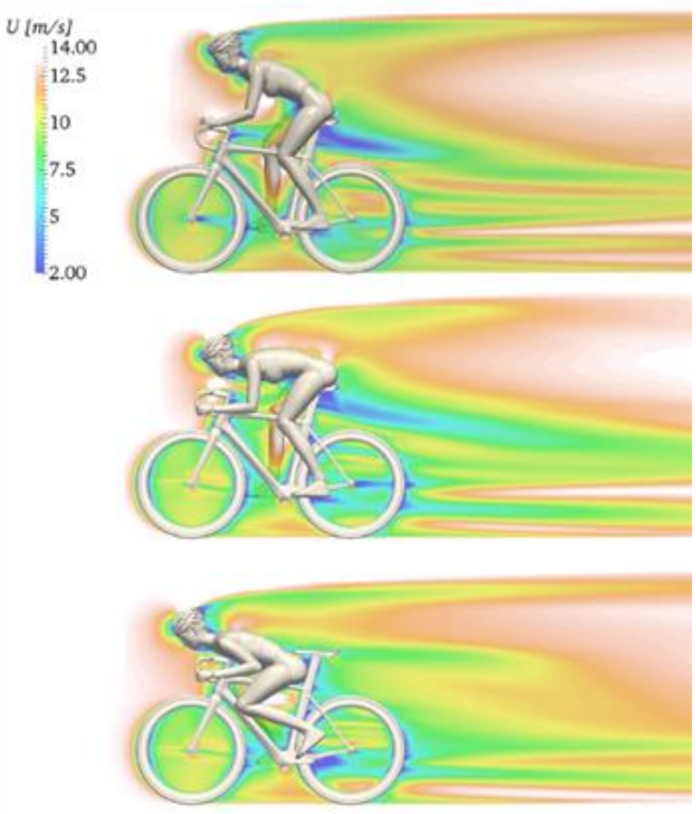
Sports Performance

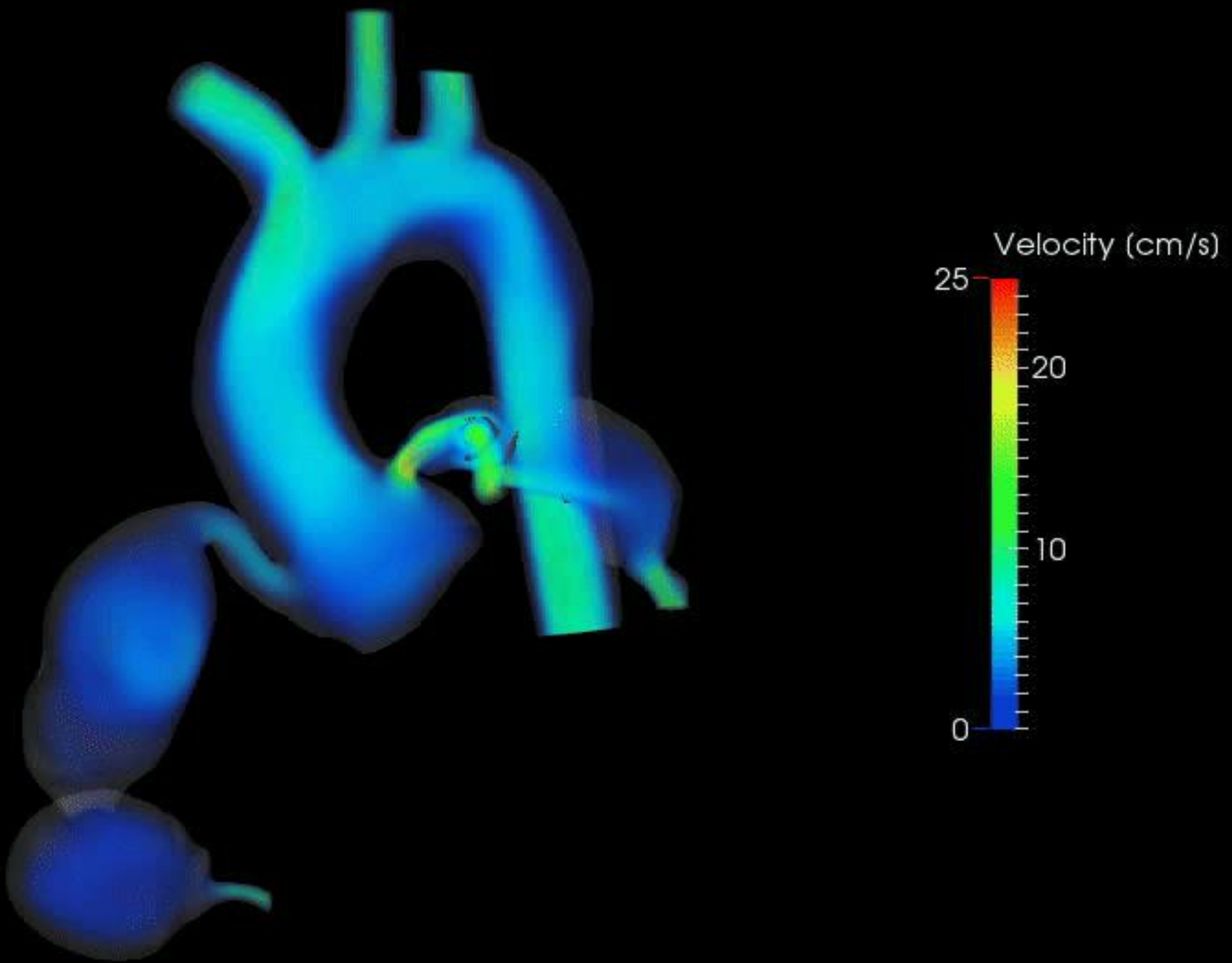


Pressure contours around an elite male swimmer wearing a LZR RACER suit in the glide position

www.ansys.com

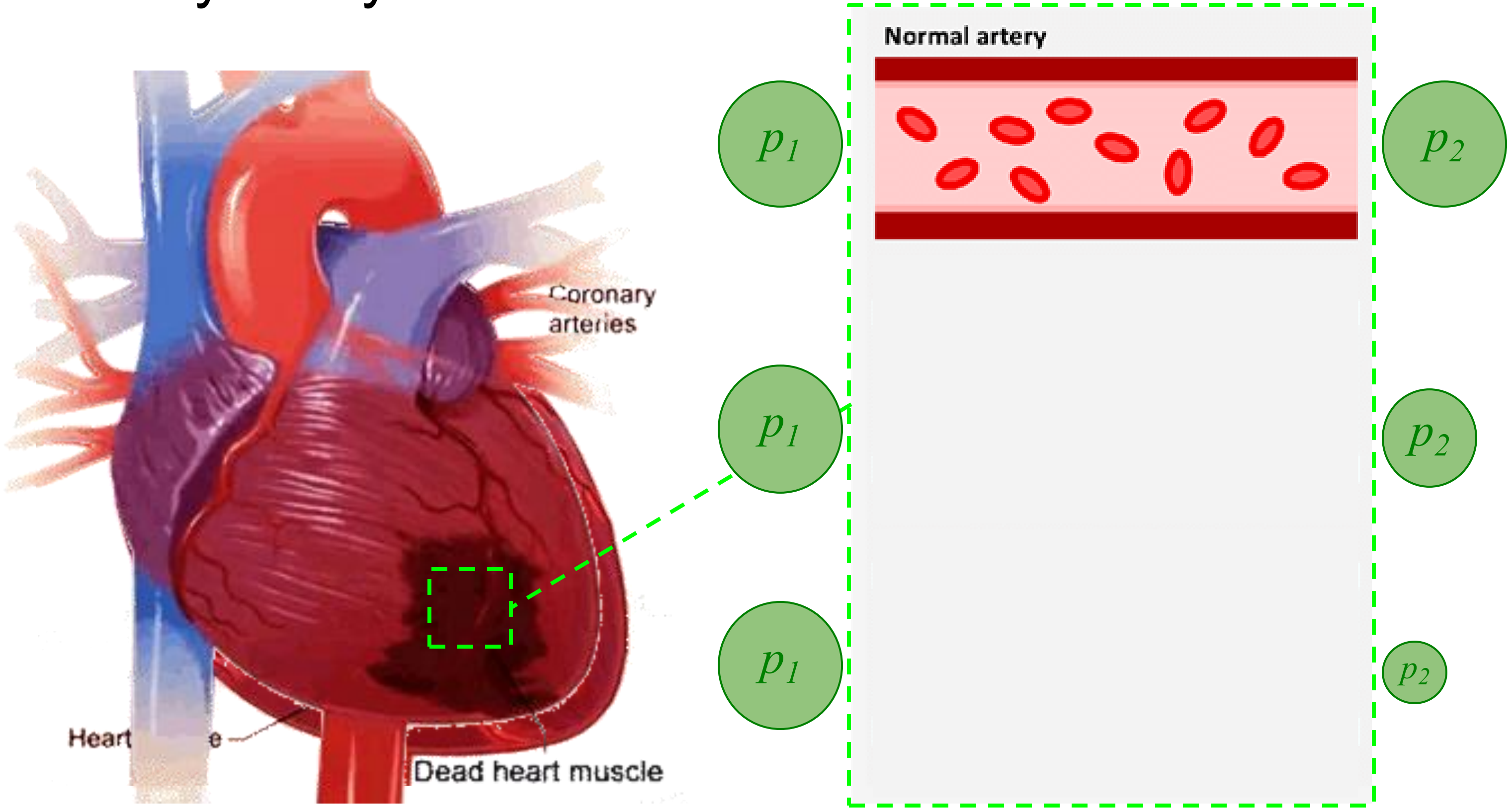
ANSYS Advantage • Volume II, Issue 2, 2008



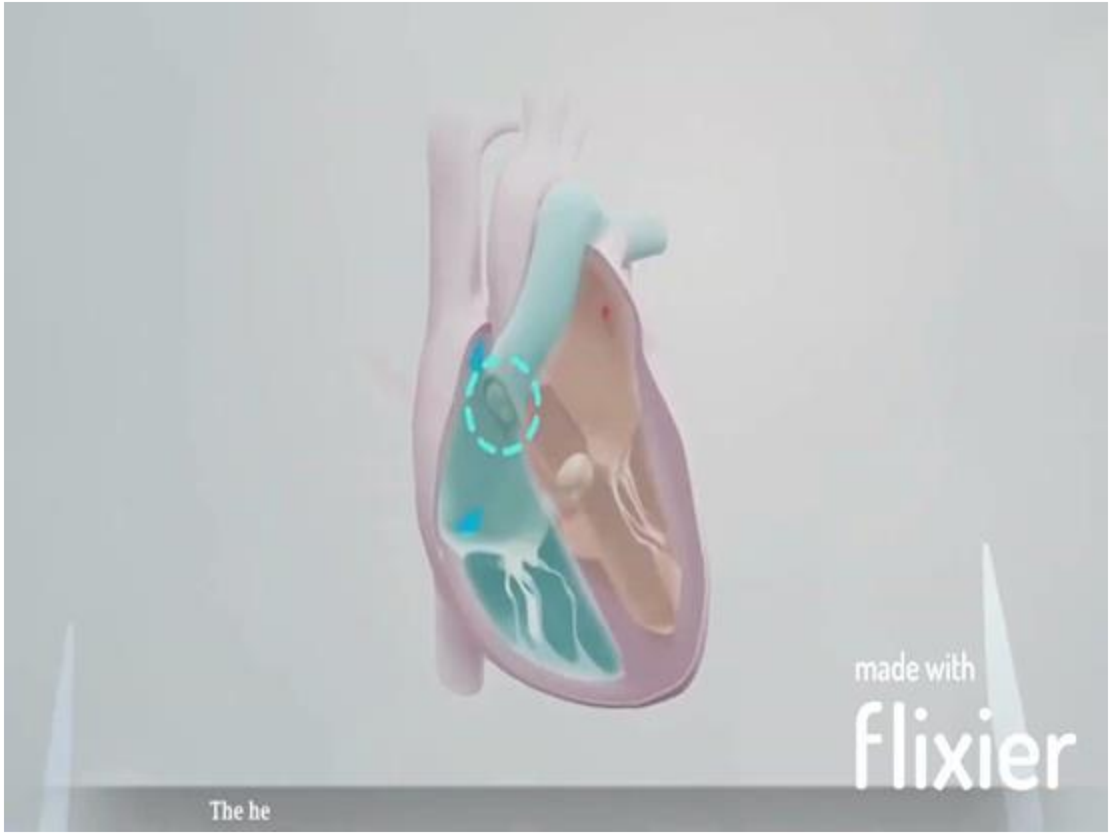

Velocity (cm/s)
25
20
10
0

How are fluid mechanics and CFD used to diagnose and treat cardiovascular disease?

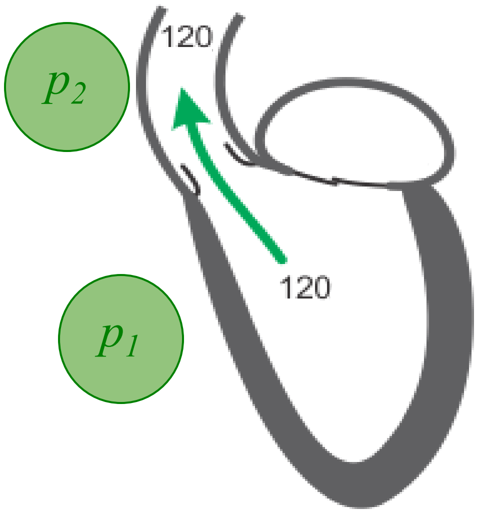
Coronary artery disease



Aortic valve stenosis

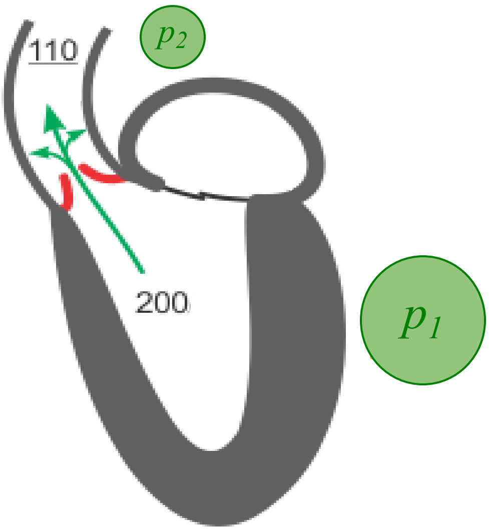


Aortic valve stenosis



Normal

$$p_1 - p_2 = 120 - 120 = 0 \ mmHg$$

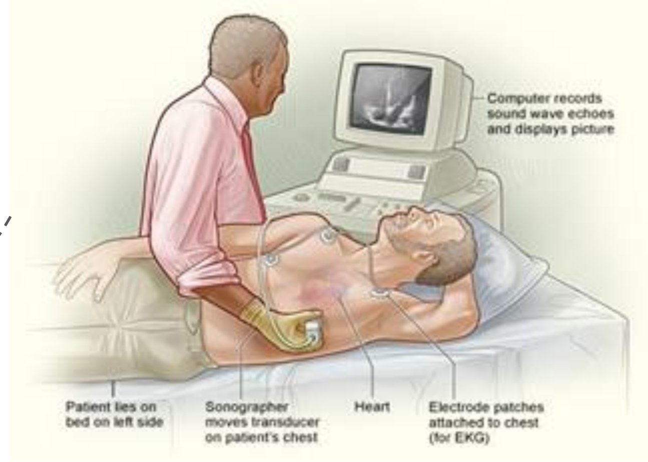


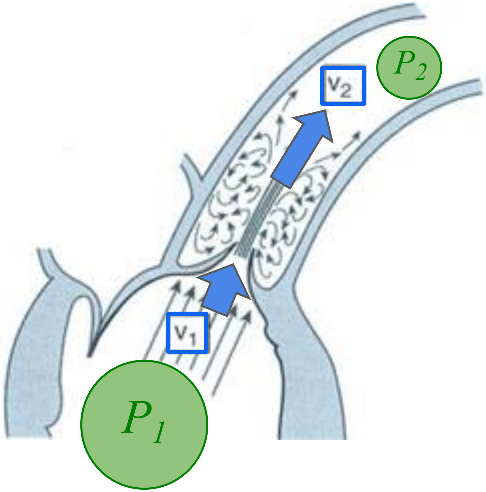
Aortic Stenosis

$$p_1 - p_2 = 200 - 110 = 90 \ mmHg$$

Measuring pressure inside someone’s heart is **hard!**

Application of Bernoulli's Principle



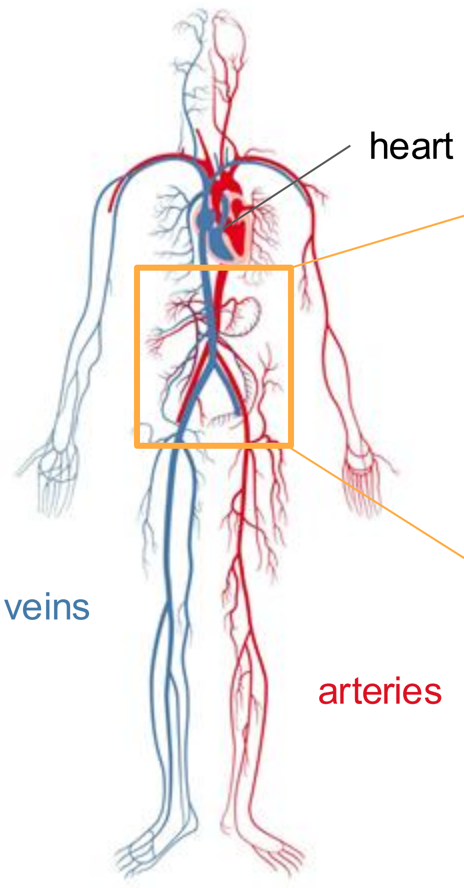


Echocardiography uses sound waves to create images of our heart and to measure blood velocity (**Doppler effect**)

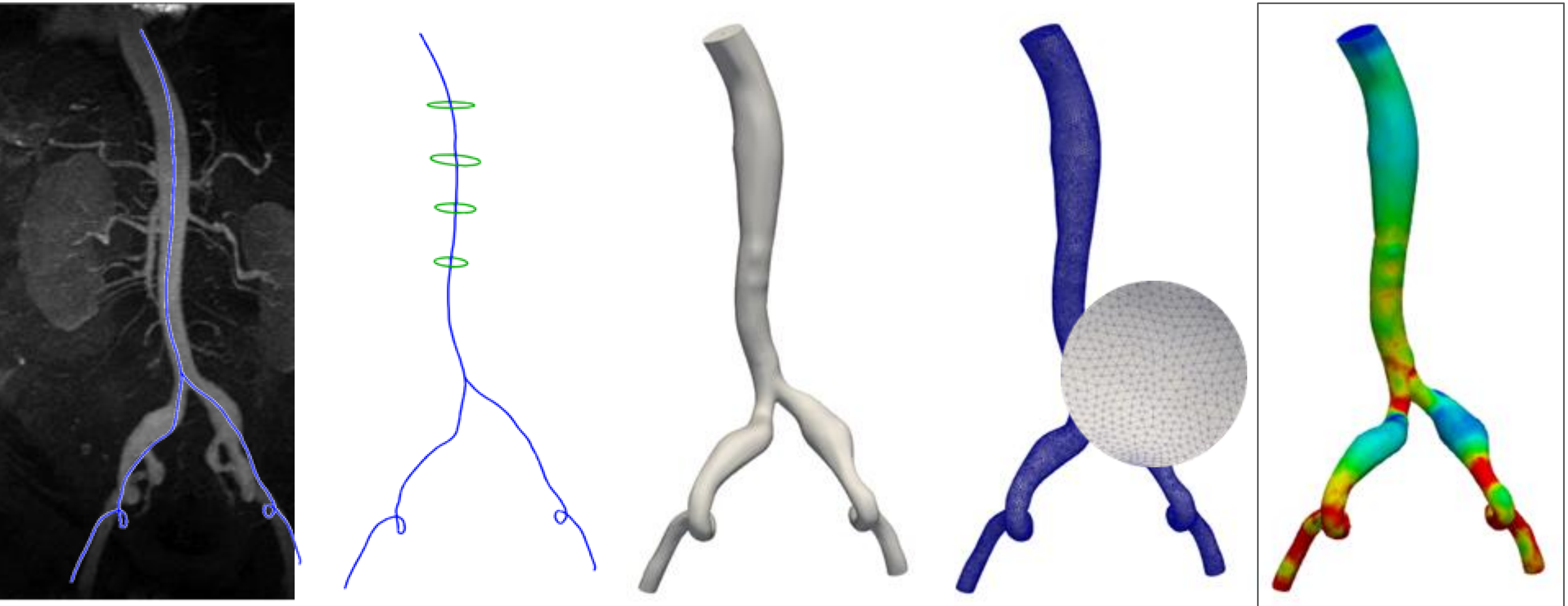
We can measure v_1, v_2 !

$$p_1 - p_2 = \frac{1}{2}\rho(v_2^2 - v_1^2)$$

Tutorial - Using computer simulations to understand cardiovascular disease



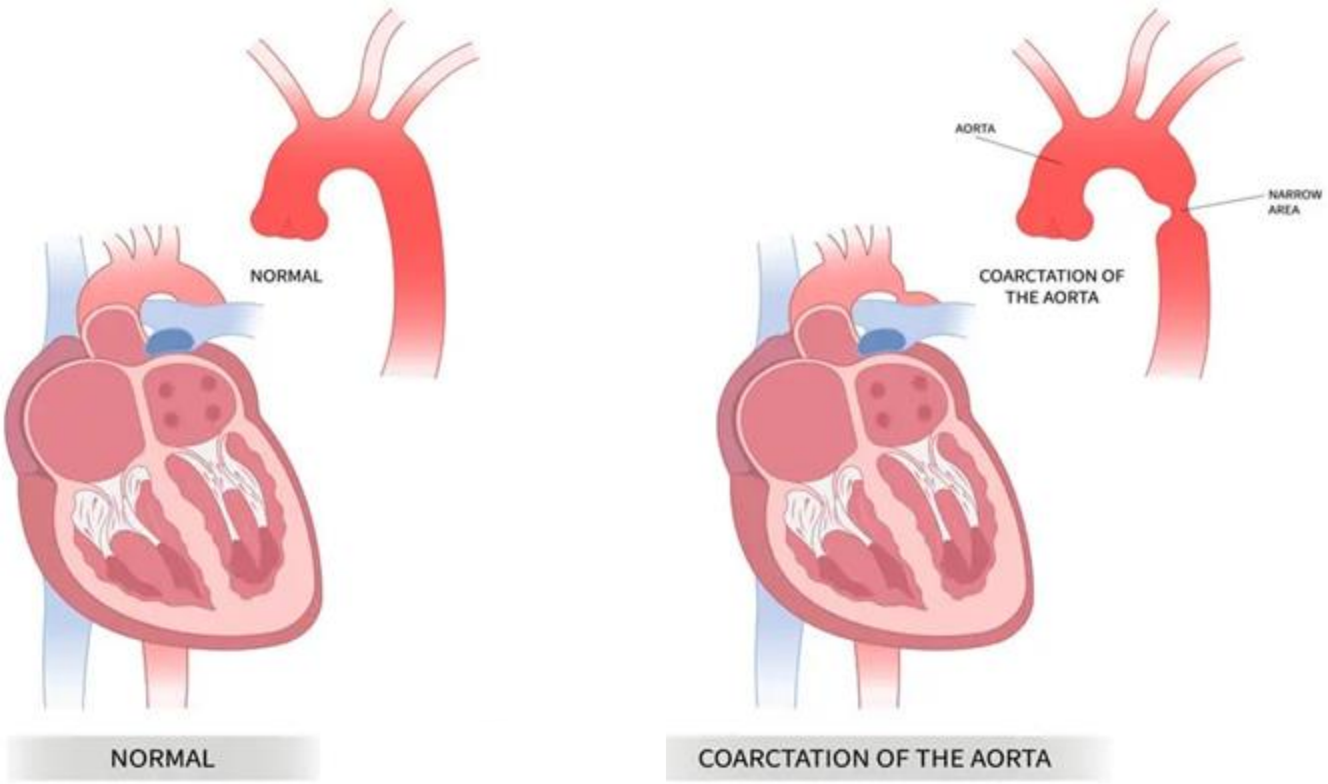
X-Ray images of arteries

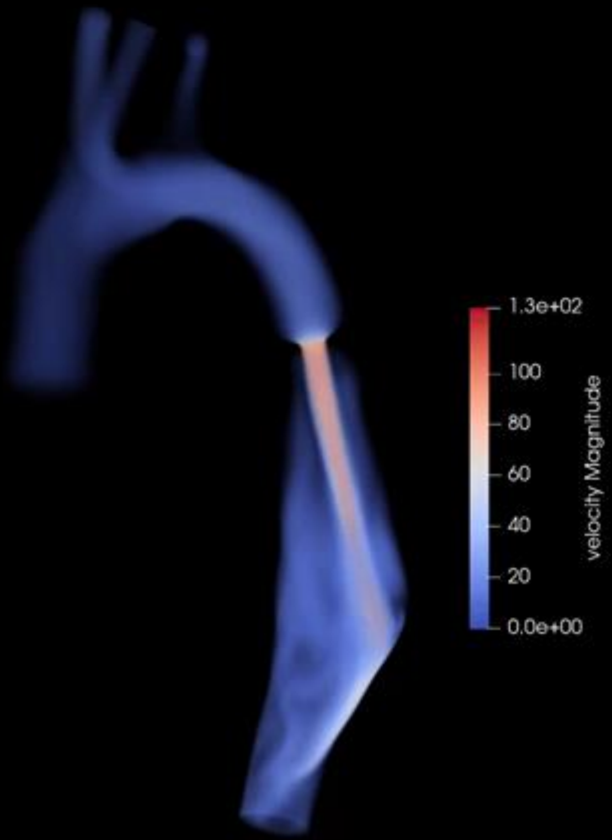


PATH | SEGMENTATIO N | GEOMETRIC MODEL | MESH | SIMULATION

We will post-process (analyze) our simulation data

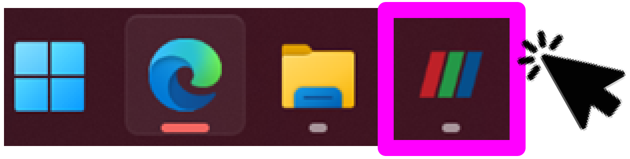
Disease: Aortic Coarctation



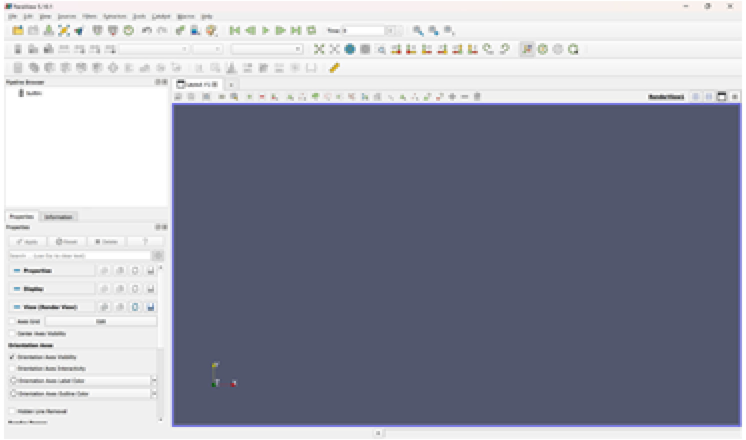

1.3e+02
100
80
60
40
20
0.0e+00
velocity Magnitude

Using paraview to look at CFD simulations!

1. Click the paraview symbol on your computer’s task bar



1. You should see something that looks like this:

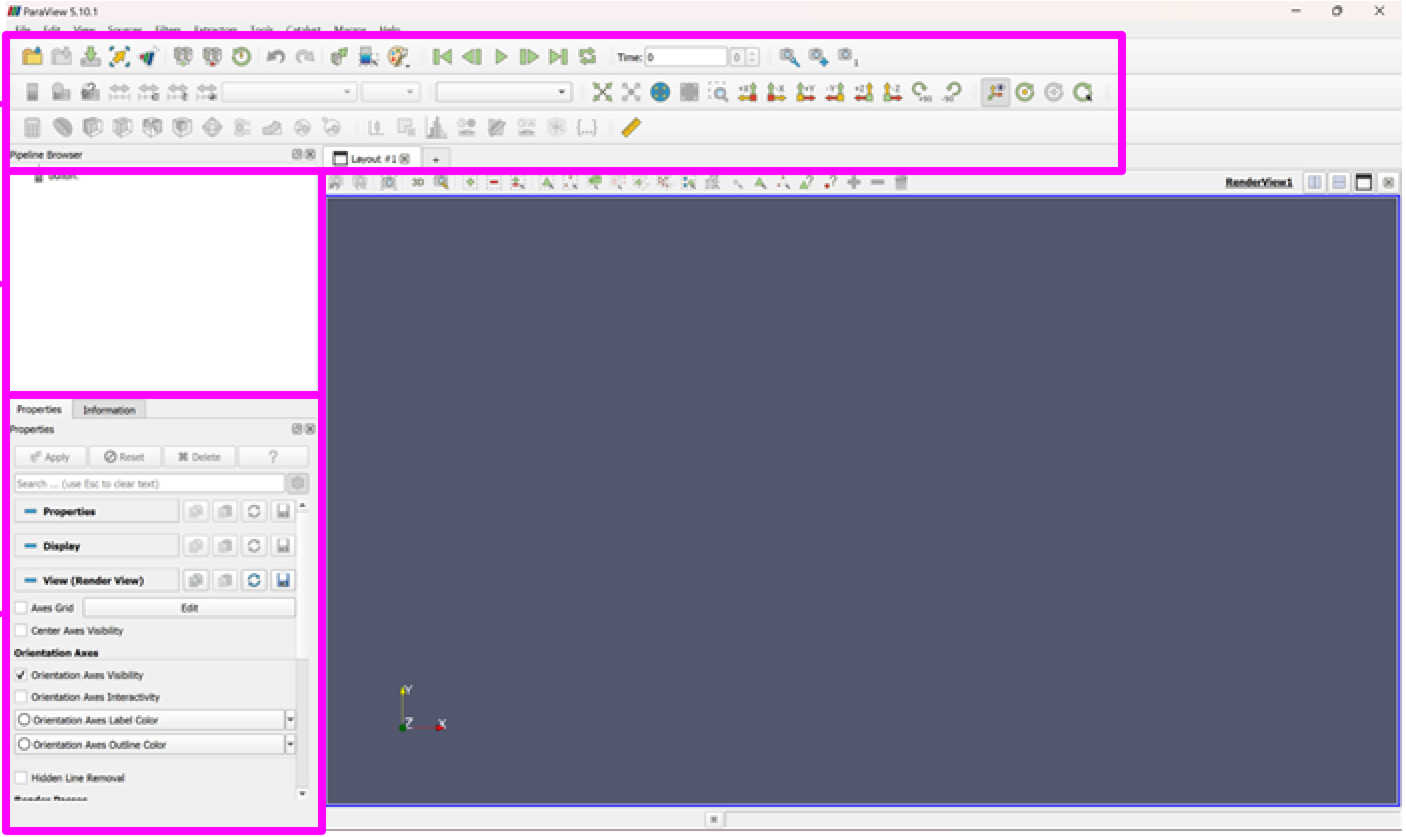


Using paraview to look at CFD simulations!

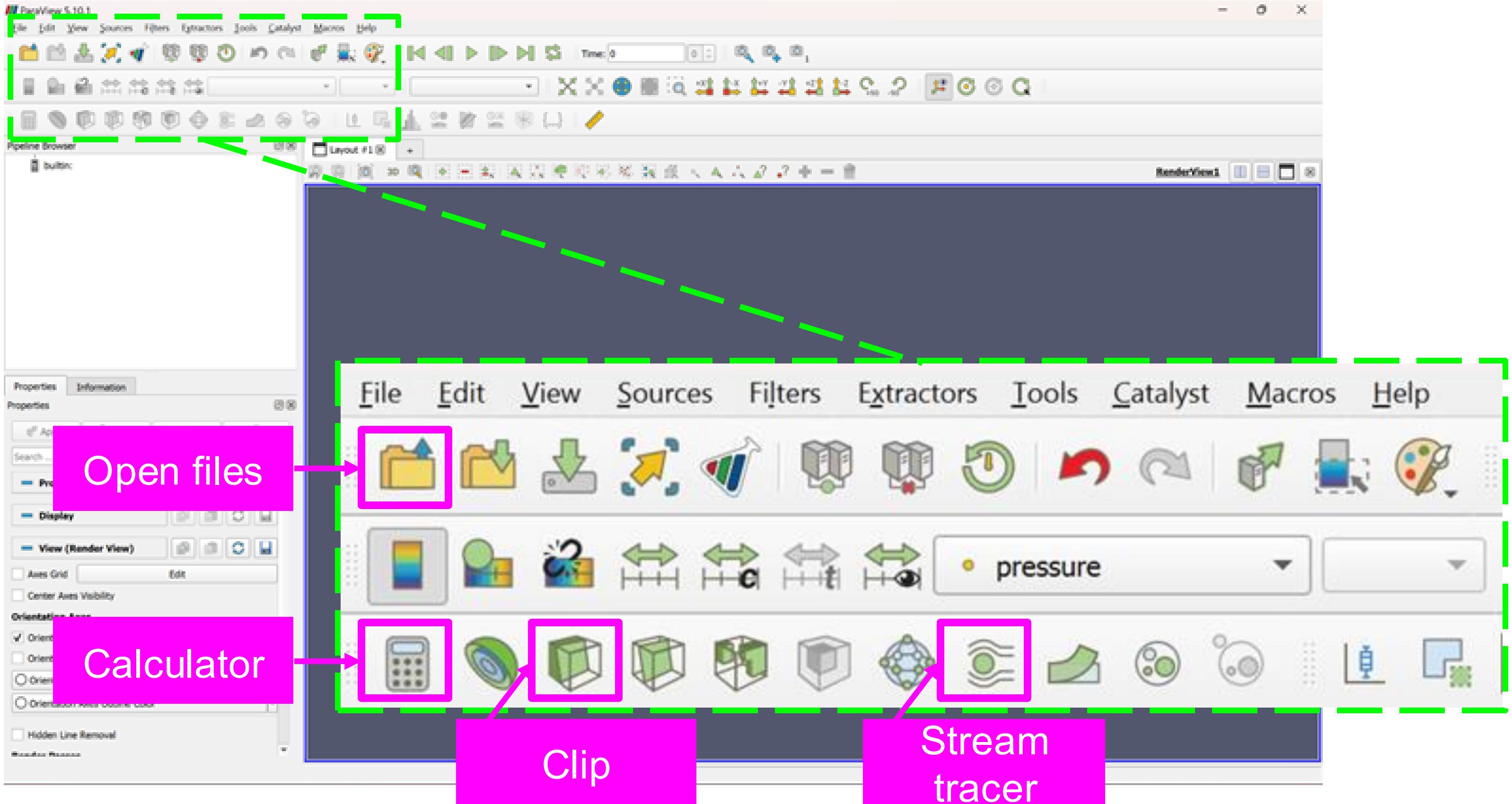
Buttons for common tools we will use

Pipeline browser: where our aorta models and modifications are

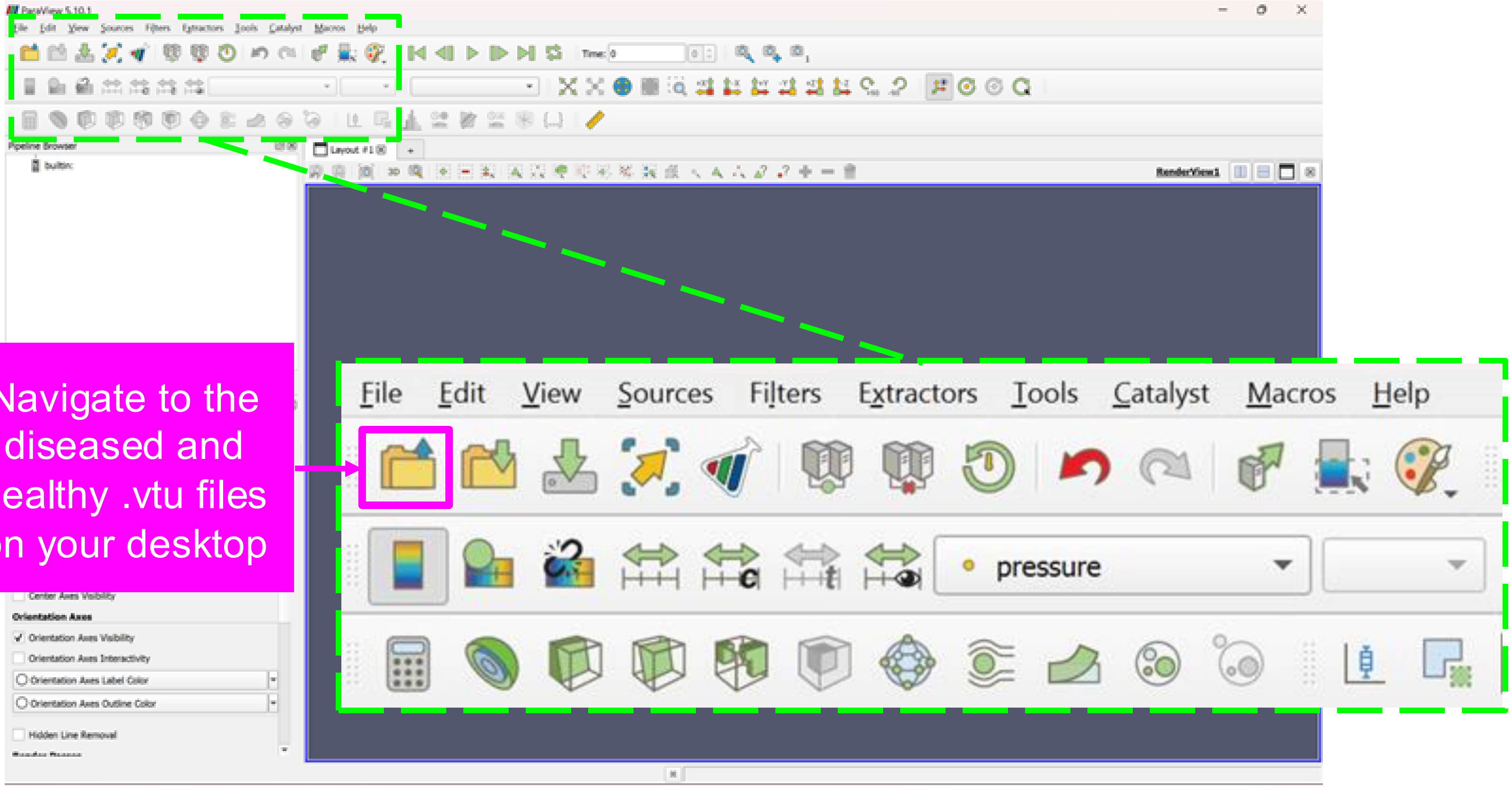
Properties: where we will control how we change our aorta model



Important buttons in Paraview

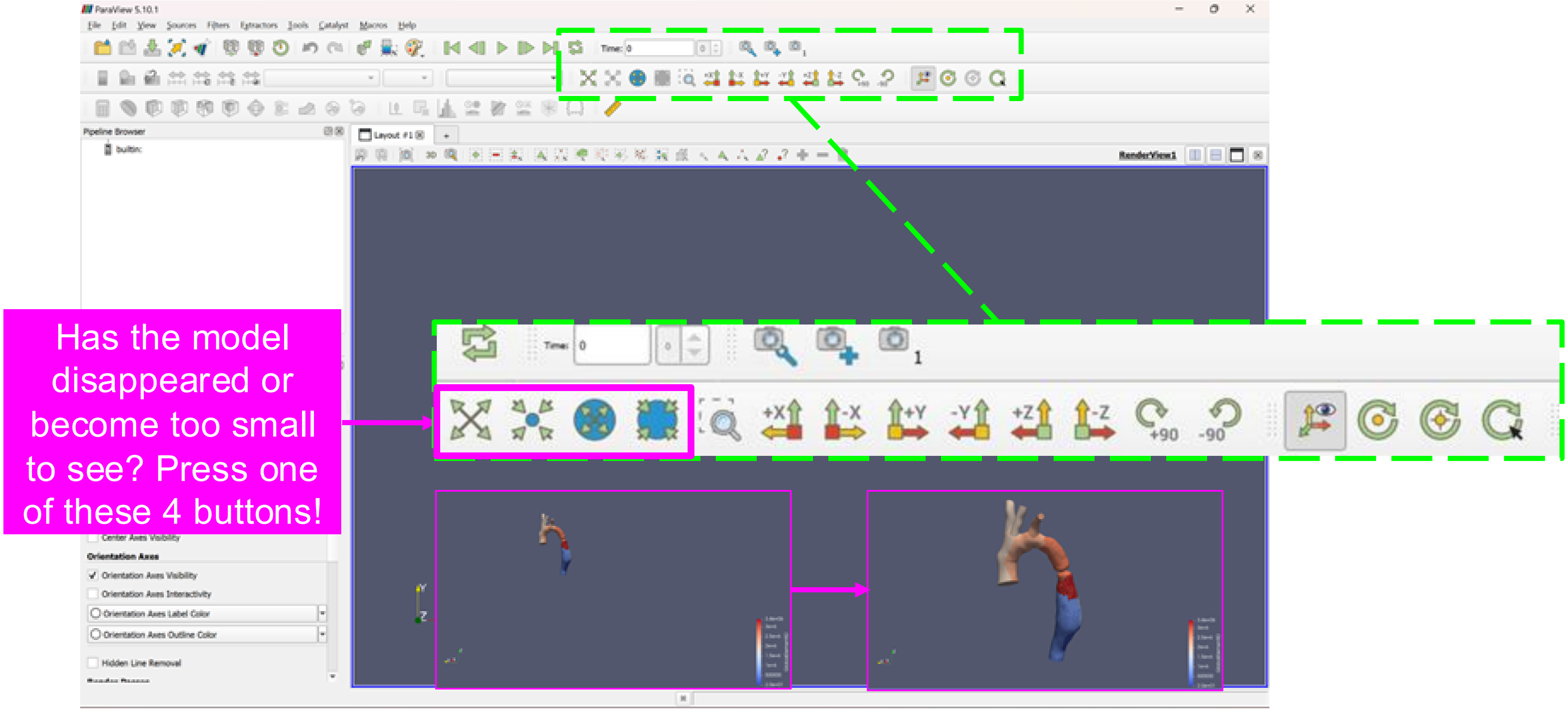


Loading data into Paraview

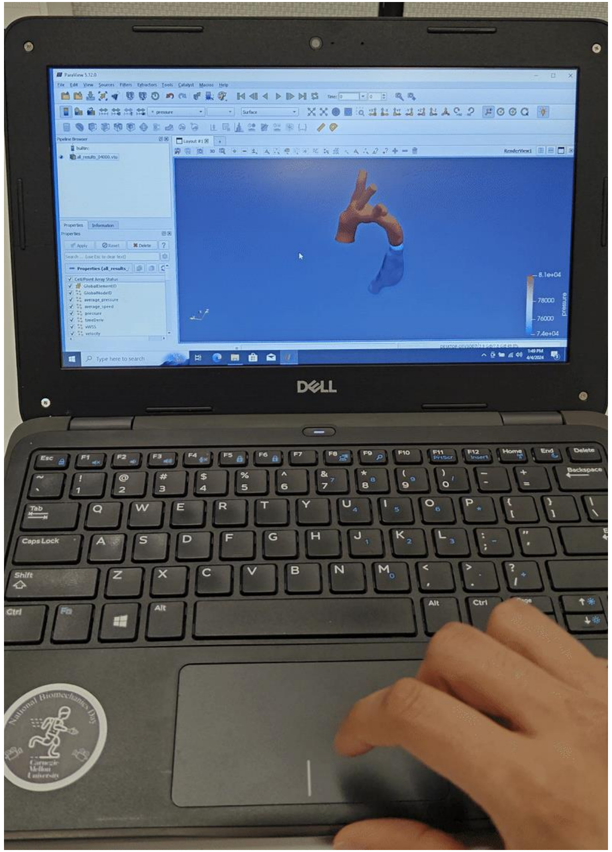


Navigate to the diseased and healthy .vtu files on your desktop

Zooming back into your aorta model

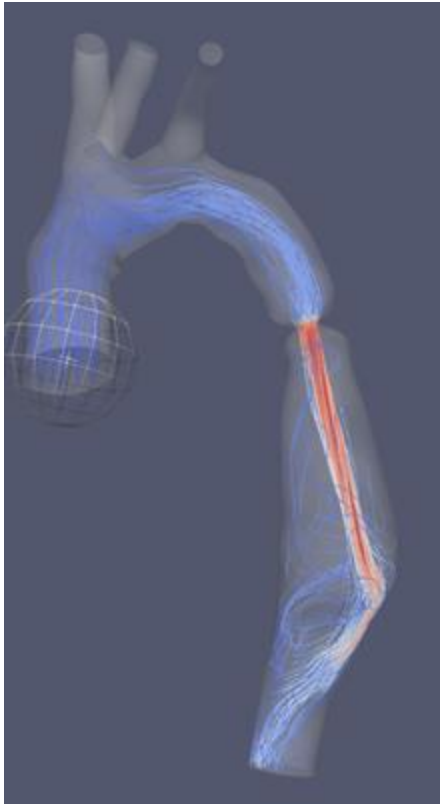


Zooming into your data and rotating it

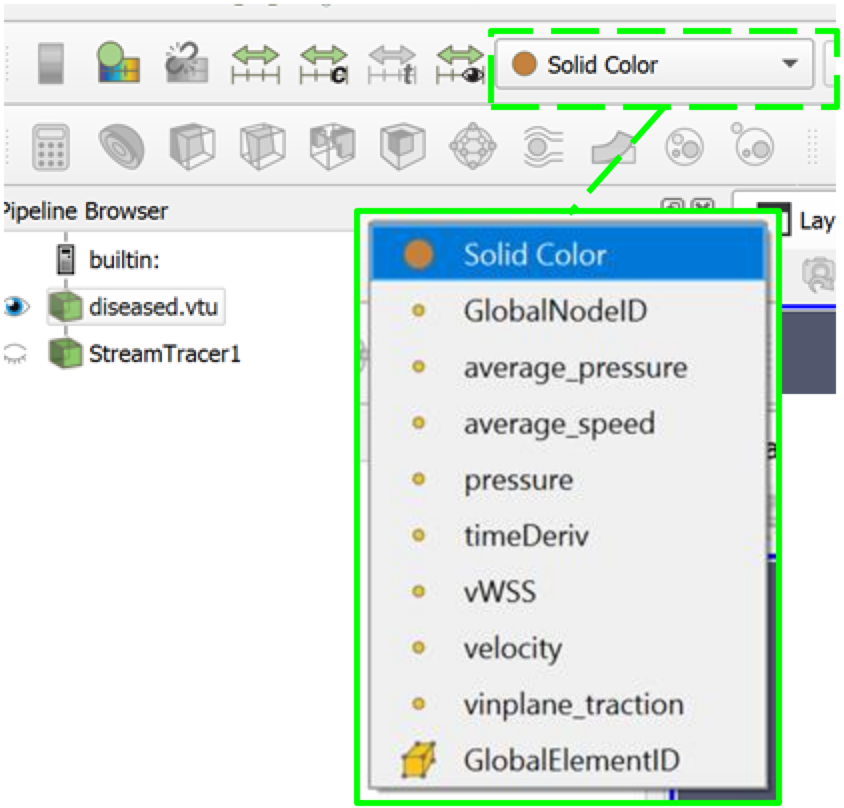


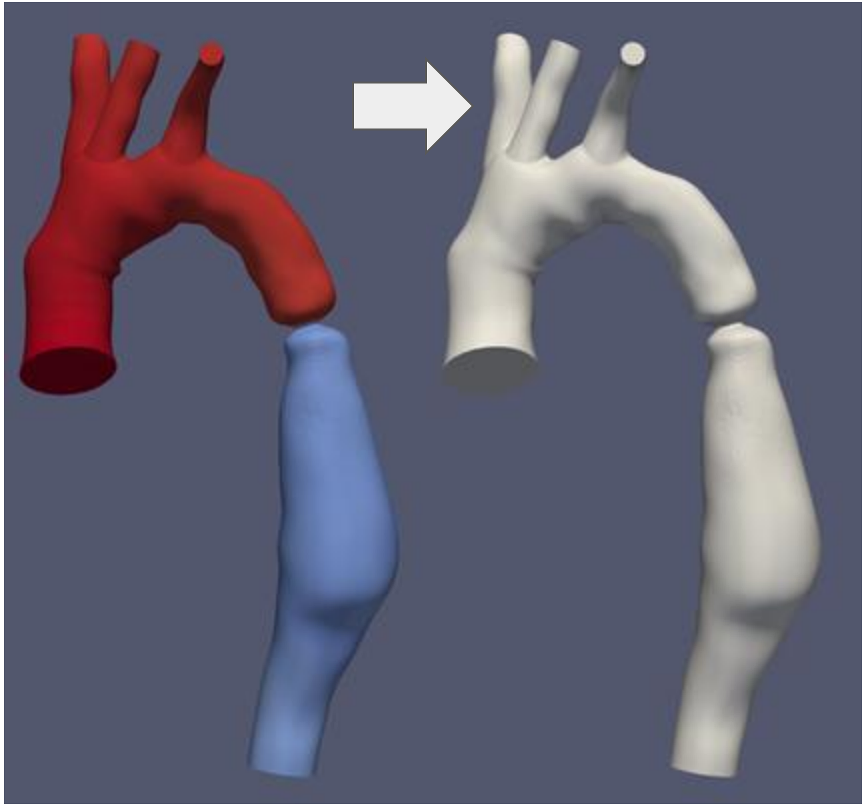
Viewing Streamlines

Looking at streamlines tells us a lot about the flow! But getting our software to show this takes some steps.

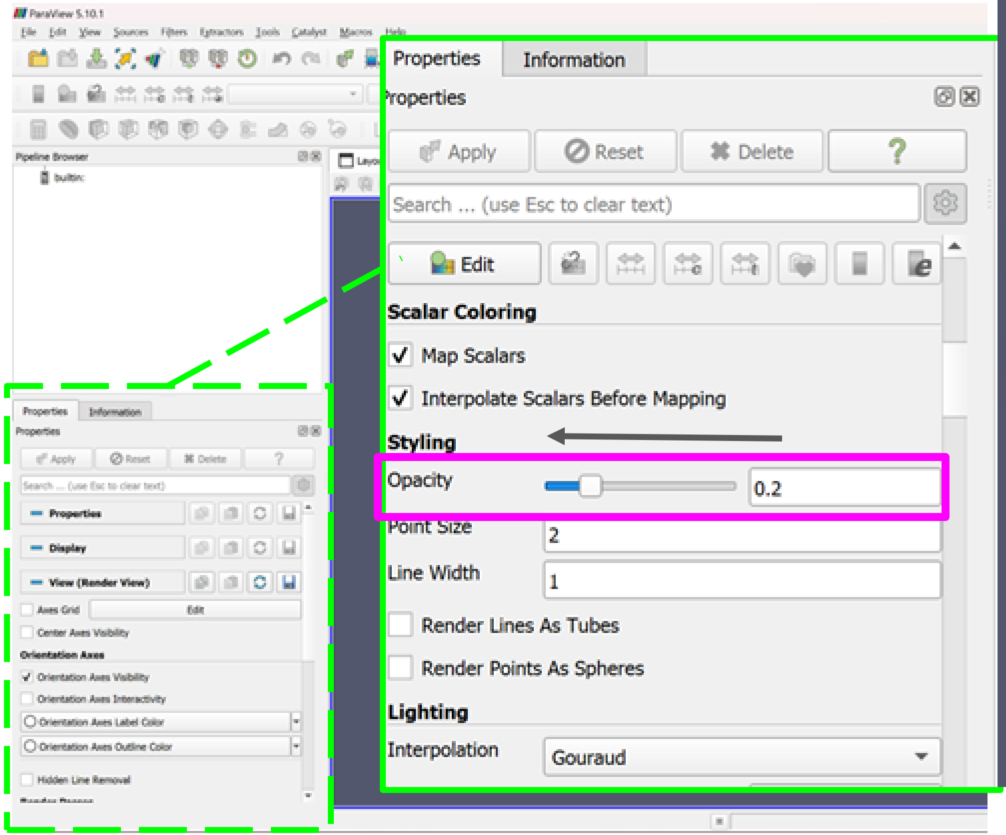


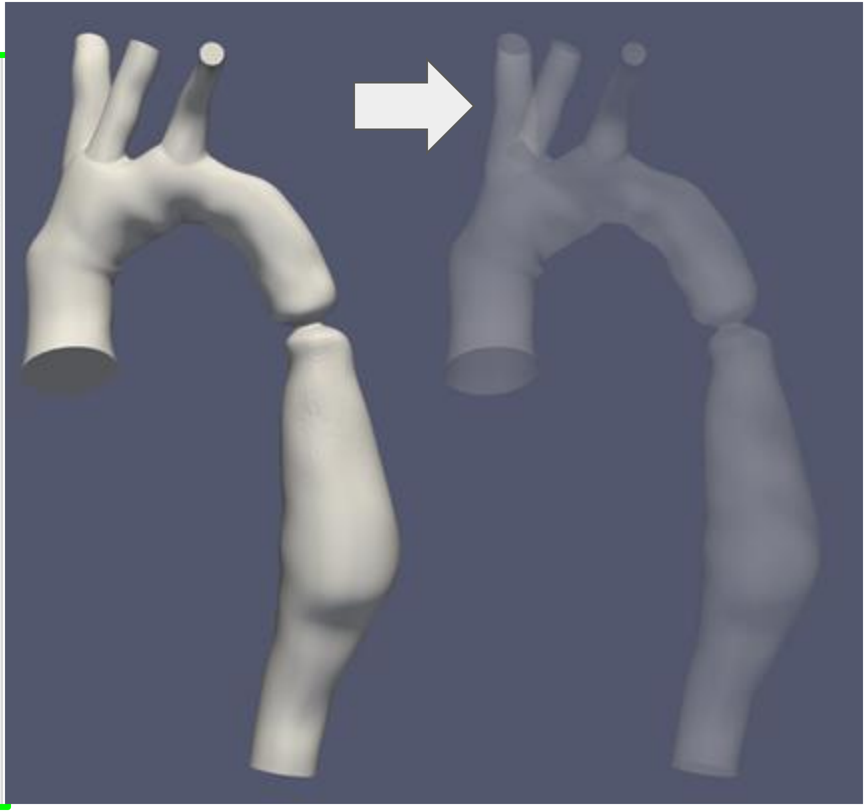
1. change to solid color



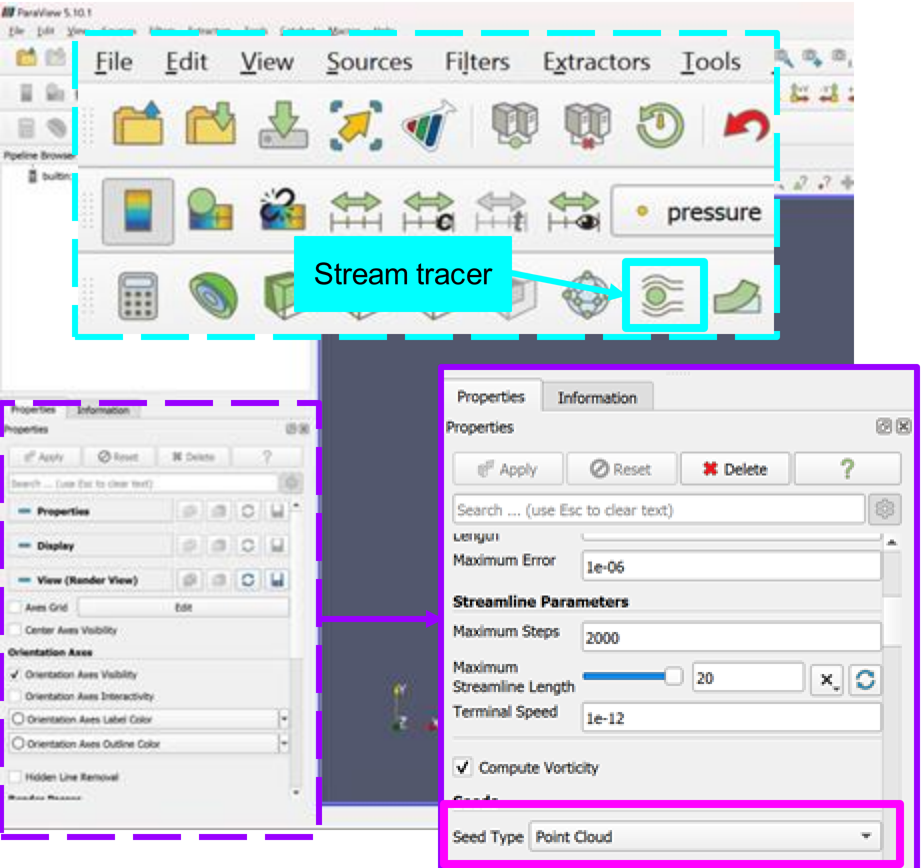


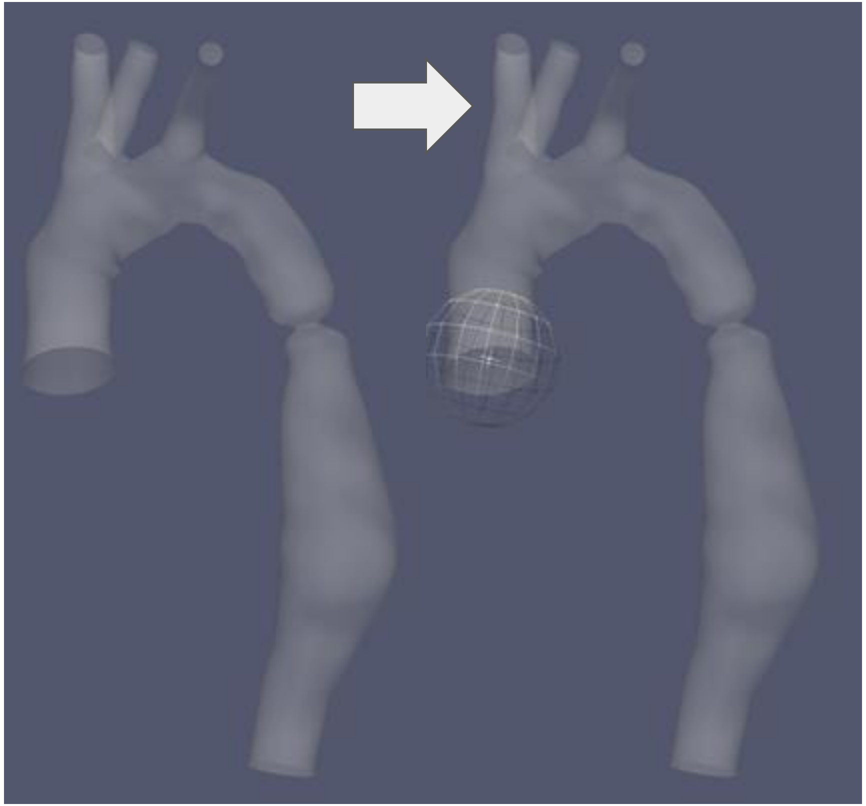
2. Change opacity to 0.20





3. Click stream tracer and set seed type to point cloud





4. Change some settings for the streamlines, then apply!