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The Use of CFD Simulations in Learning Fluid Mechanics at the Undergraduate Level

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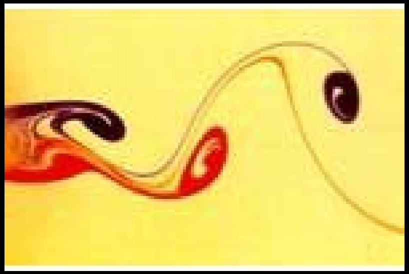
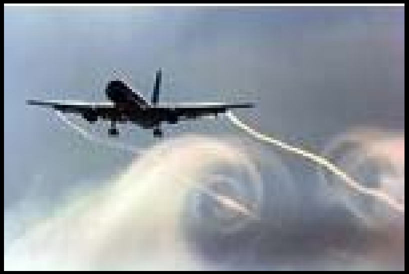
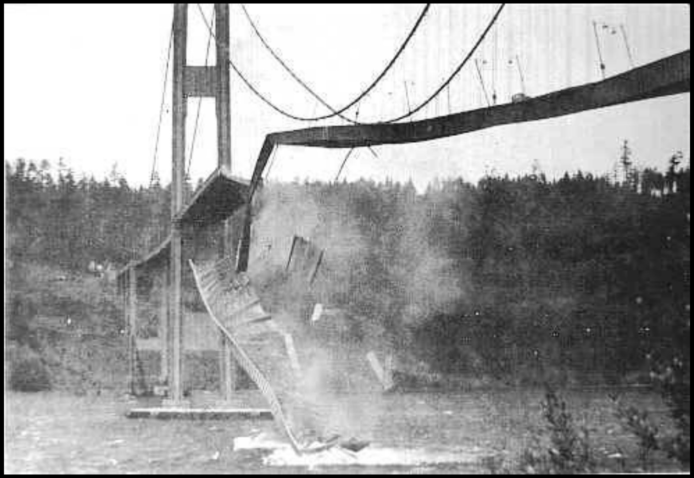
Fluid Mechanics

- Fluid flows can be beautiful, amazing,







- and destructive.

Source: eFluids.com

A Traditional CFD Course

- Basic methods:
  - Finite difference, volume, or element.
  - Volume of fluid, level-set, phase field, etc.
- Gridding or meshing.
- Pressure-velocity coupling.
- Upwind differencing, artificial diffusion.
- Concentrate on numerical technique.
- Write your own code.

CFD for Fluid Exploration

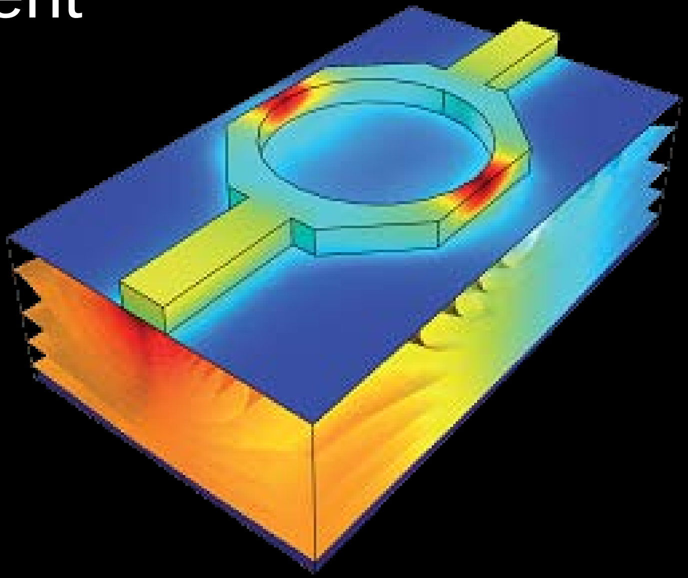
- Design a senior elective course that explores fluid flows using CFD as a tool.
- Use COMSOL Multiphysics as a PDE solver, but not a black box.
- Learn to properly pose the mathematical model.
- Learn to find and assess an accurate and reasonable solution.
- Explore the difference between modeling and reality.
- Develop a feel or intuition for the physics.

Course Content

- Three credit-hour semester course.
- Two lectures (as needed) & one lab per wk.
- FEM lectures (two weeks).
  - One programming assignment on FEM.
- COMSOL tutorial (one week).
- Seven labs on different fluid flows (1 or 2 weeks each).
- One final project (one month).

Laboratory Manuals

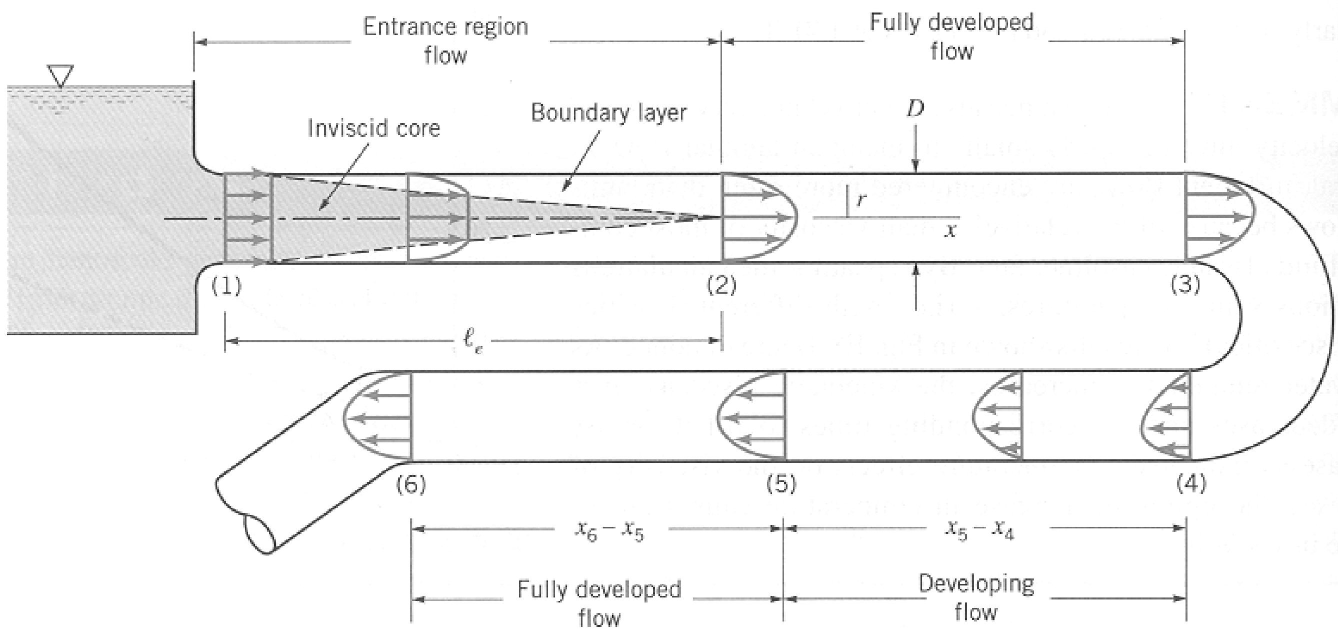
- Introduction and use of COMSOL software.
  - Lab 0: Steady electric current and heat generation in an aluminum film on a silicon substrate.
    - Thank you, COMSOL!



- All labs written in a tutorial form with decreasing level of detail from Labs 1 to 7.

Developing Flow in a Channel

- Commonly studied in most introductory fluid mechanics courses.



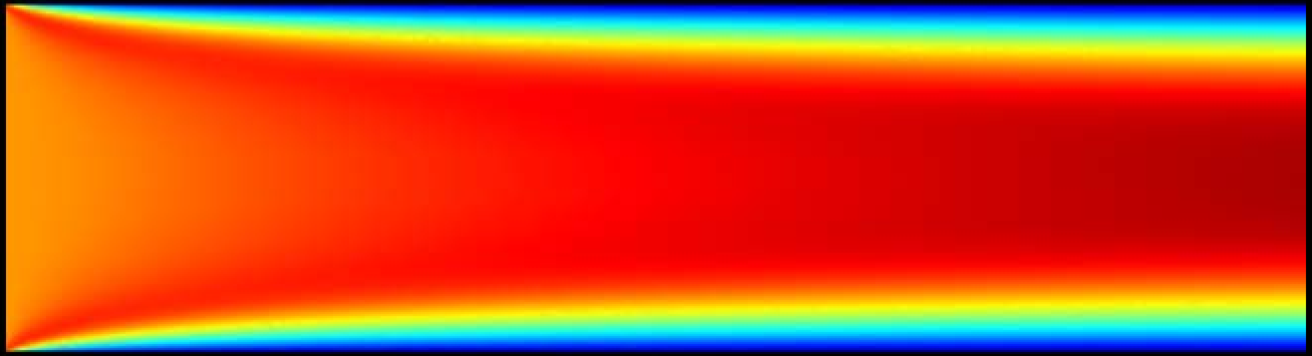
■ FIGURE 8.5 Entrance region, developing flow, and fully developed flow in a pipe system.

"Fundamentals of Fluid Mechanics," Munson, Young, Okiishi, and Huebsch, 6th ed.

Developing Flow in a Channel – 2

- Examine developing and fully developed velocity profiles.
- Measure entrance length: $\frac{L_E}{h} = f\left(\frac{\rho U_0 h}{\mu}\right) = 0.06\,Re$
- Find inviscid core flow with Bernoulli's eq.
- Compare to theory and experiment.

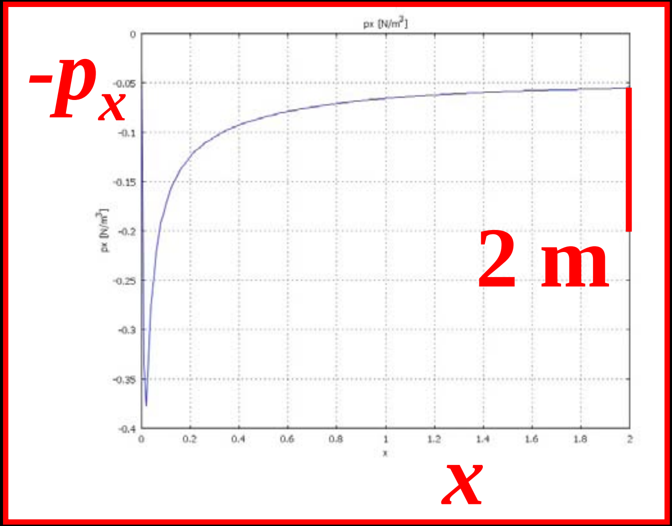
Surface plot of velocity magnitude at channel entrance.



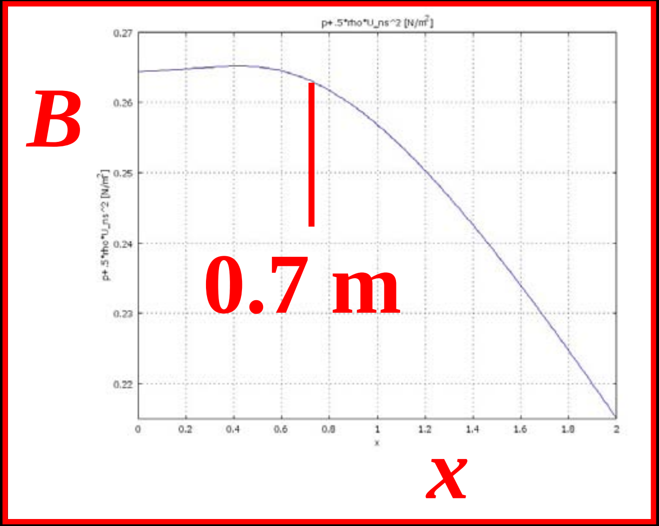
Developing Flow in a Channel – 3

- Student results: U_{avg} = 0.4 m/s, h = 4 cm

Pressure Gradient



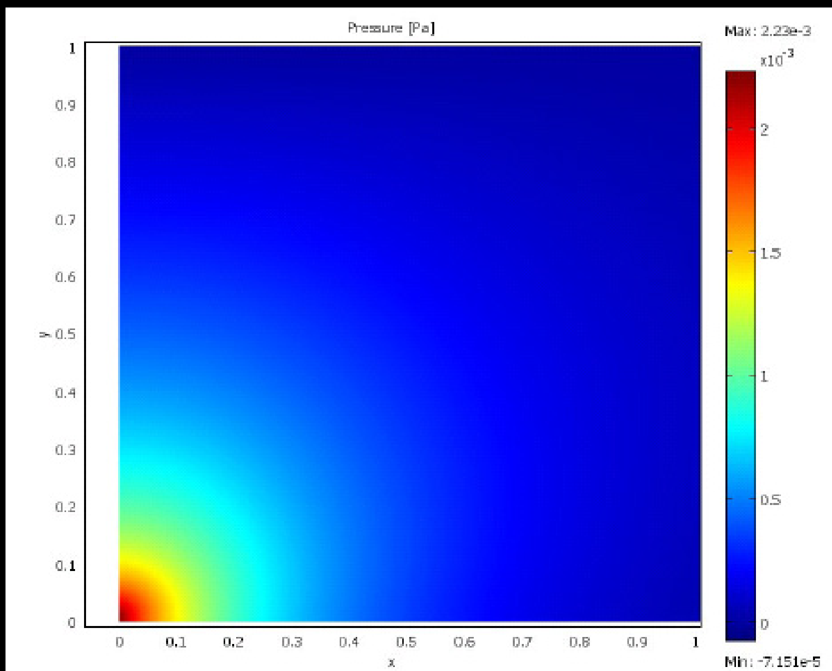
Bernoulli's Equation



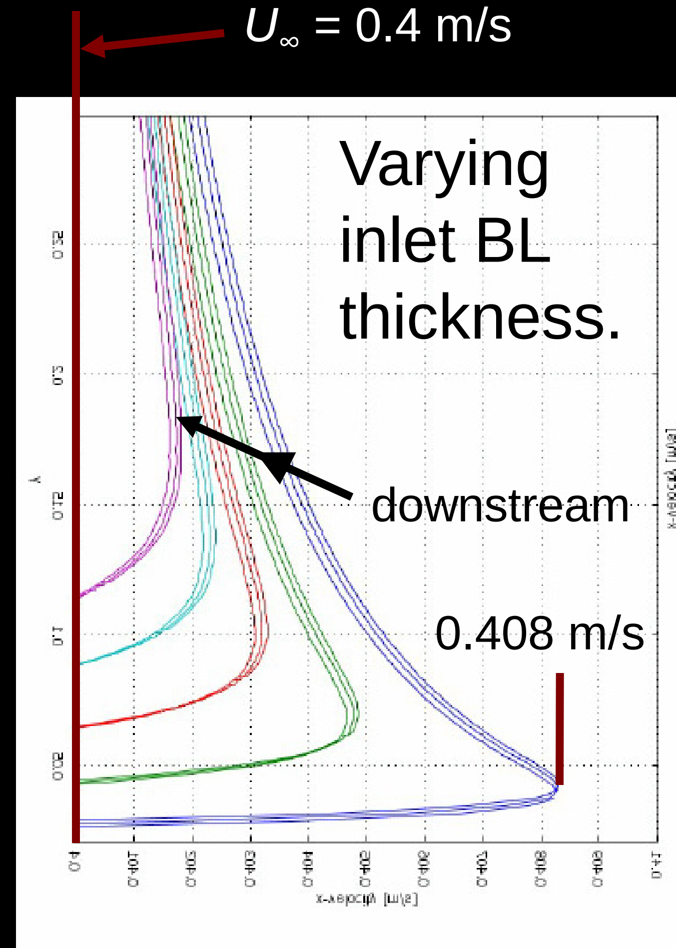
$$B = p + \tfrac{1}{2}\rho V^2$$

Developing Boundary Layer

Uniform flow past
a sharp-edged flat plate.



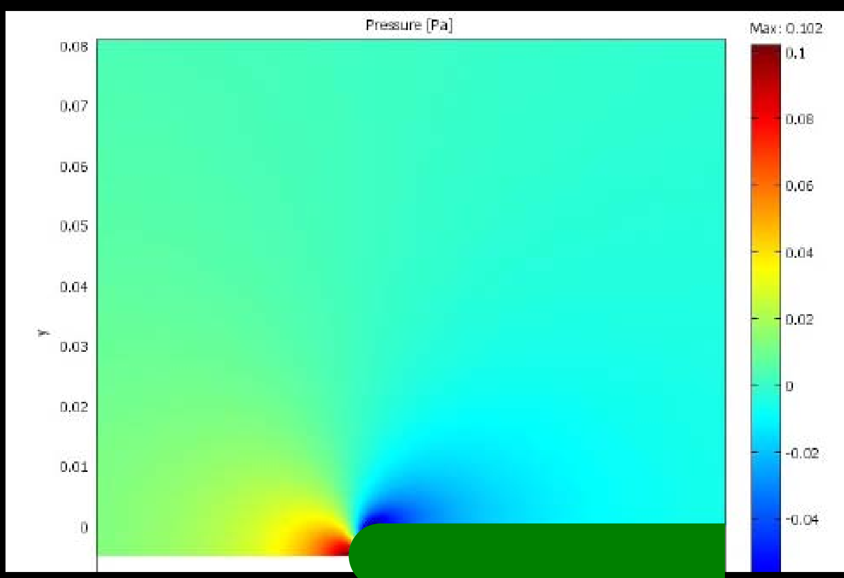
Pressure near leading edge



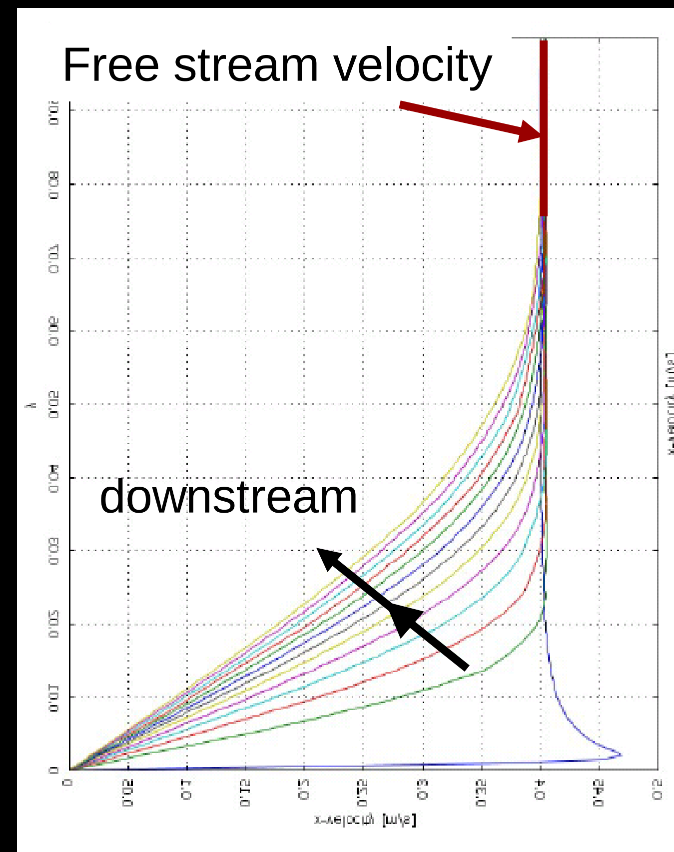
Horizontal velocity

Developing Boundary Layer – 2

Uniform flow past a round-edged flat plate.



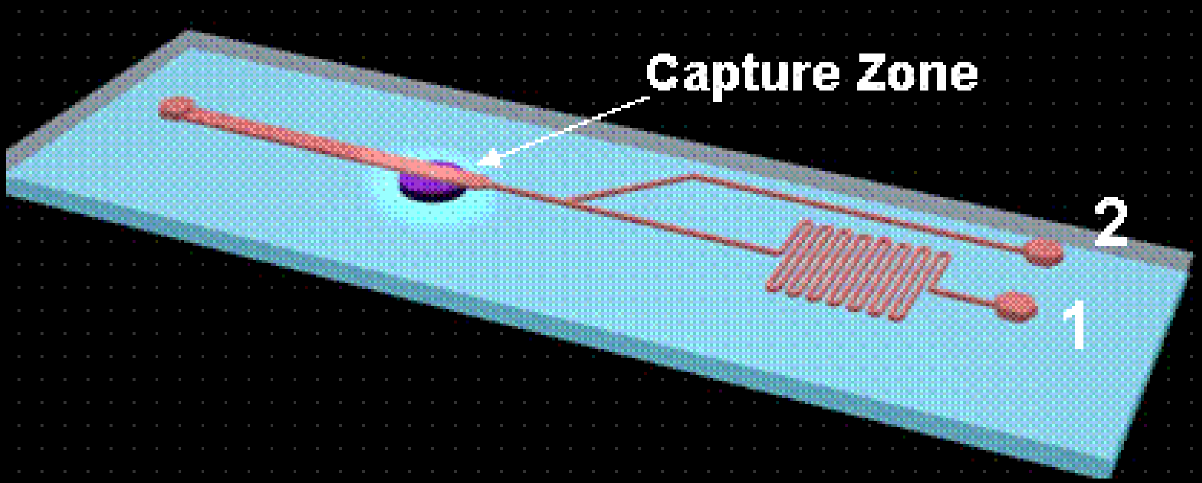
Pressure near leading edge



Horizontal velocity

Microfluidics

- Current technology of great interest.



A microfluidic fluorescence-based biosensor from IBI, Inc.
http://www.ibi.cc/microfluidics.htm

Tea Cup Experiment

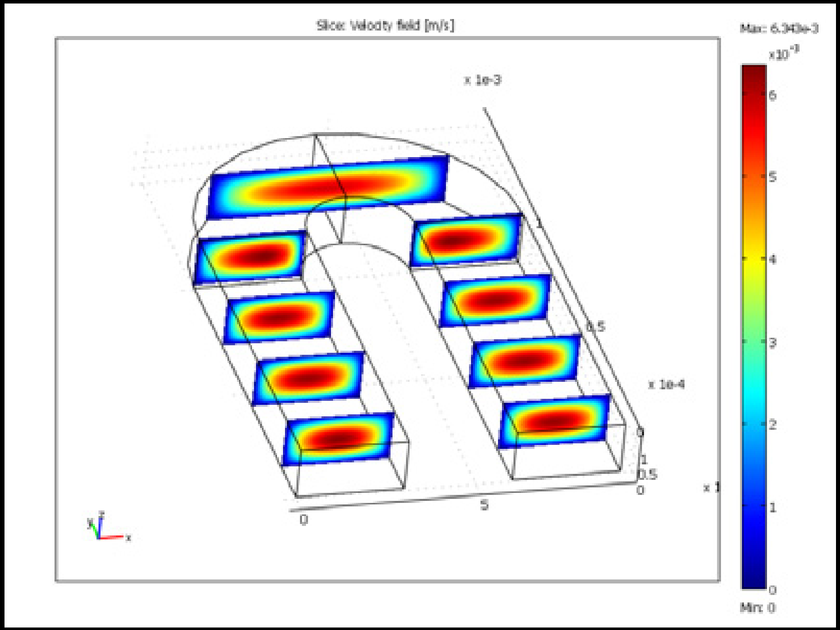
- Simple classroom demonstration.

Why does this happen?

Stirred by Hilda Elizabeth Tippette Nix

Microfluidics – Low *Re*

- Flow of water in a 180° bend.
- Cross-section: 300 μm x 150 μm.
- Uniform inlet: 0.007 m/s, ***Re*** = 0.94.

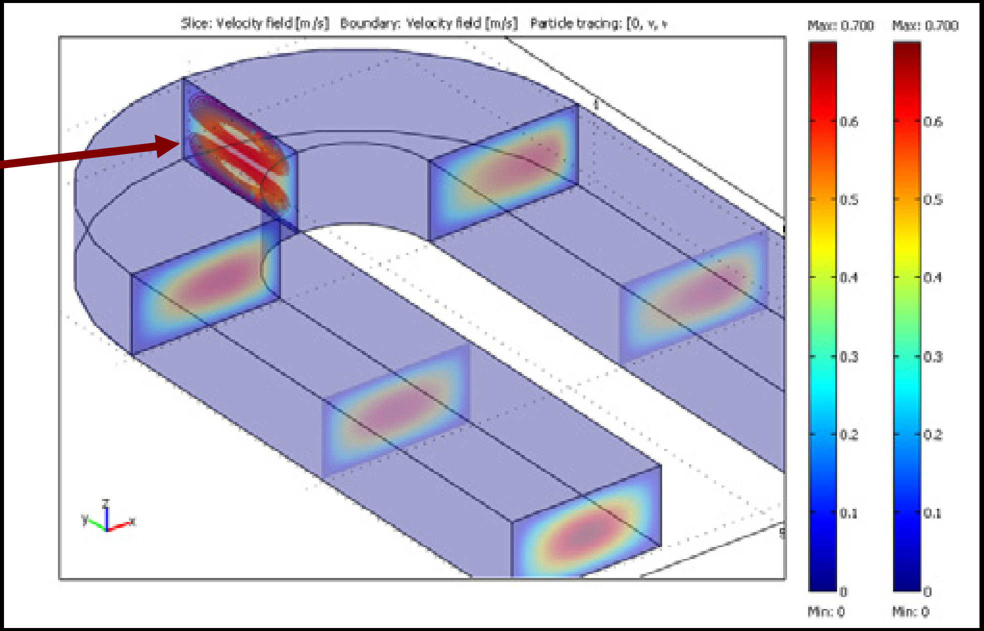


Velocity field

Microfluidics – Secondary Flow

- Flow of water in a 180° bend.
- Cross-section: 300 μm x 150 μm.
- Uniform inlet: 0.7 m/s, $\boldsymbol{Re}$ = 94.

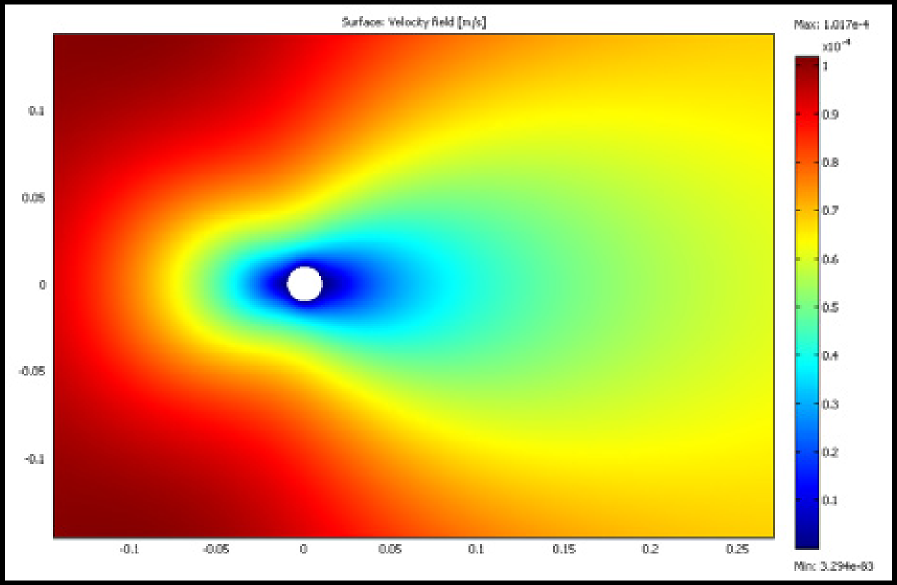
Particle traces in the plane



Velocity field

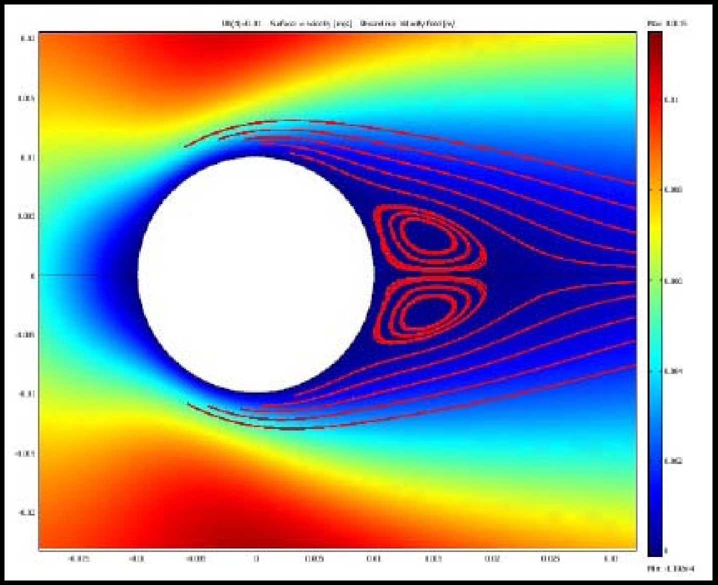
Flow Past a Cylinder

$Re = 1.37$



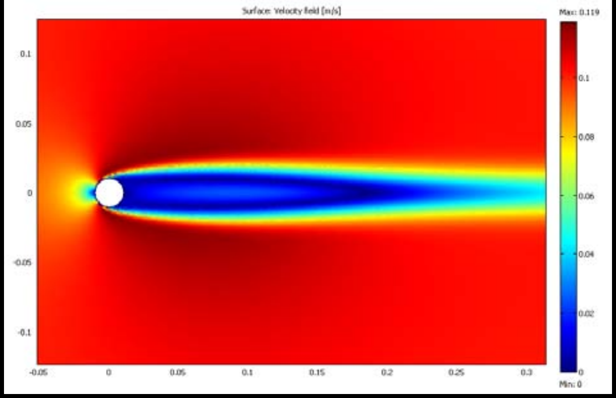
Bound vortices

$Re = 13.7$

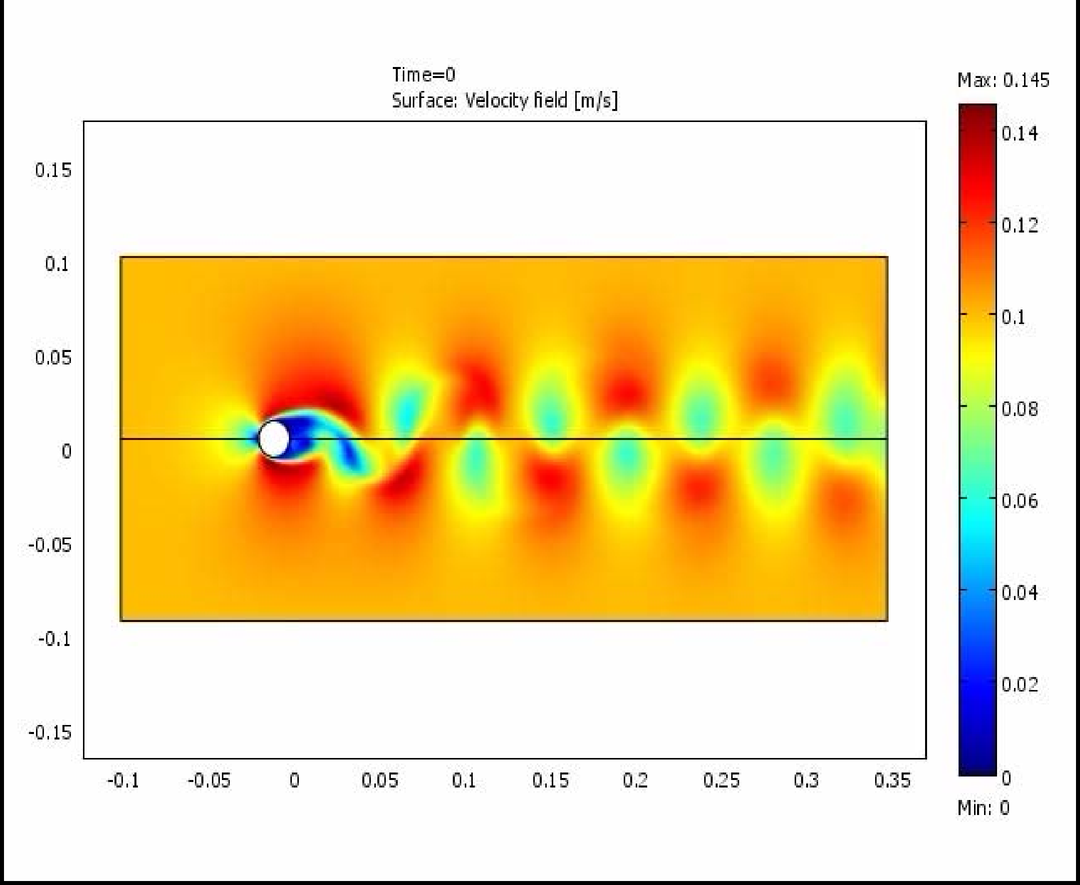


Flow Past a Cylinder – 2

Steady
Re = 137

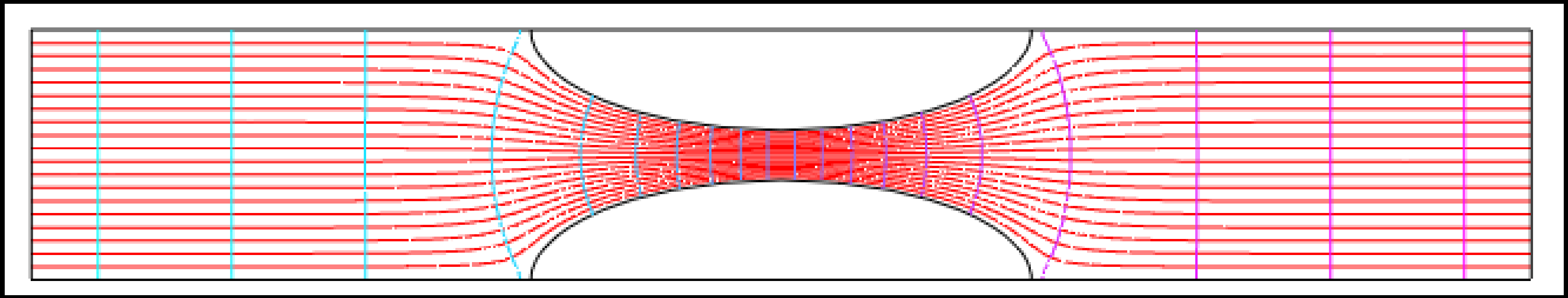


Unsteady, *Re* = 137



Potential Flow

- Potential flow in a Venturi.



Contours: potential Streamlines: velocity

- Compare flow rate to 1-D theory.
- Measure pressure at throat and upstream using point integration coupling variables.

Potential Flow – 2

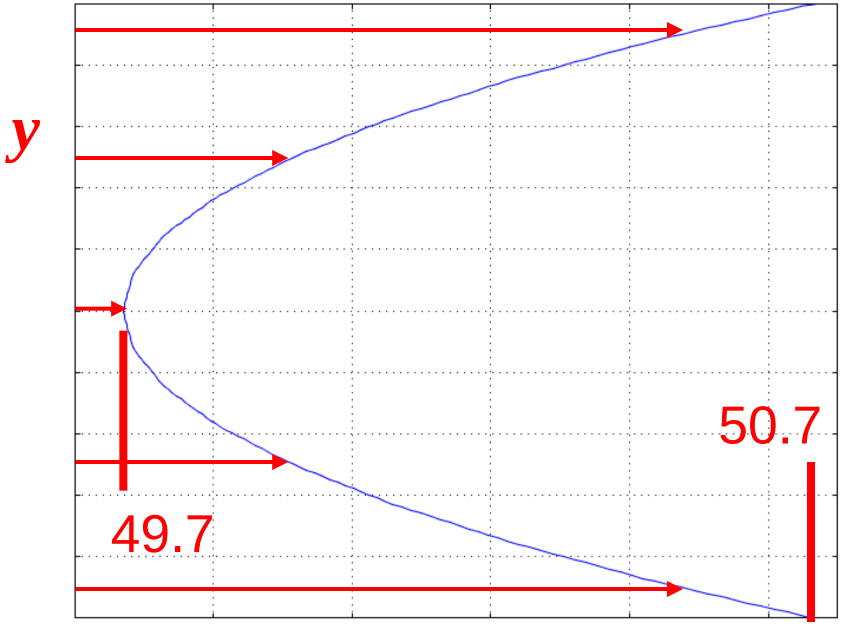
- Compare the flow rate Q to inviscid 1-D flow theory.

$$Q = \left(\frac{2\Delta p / \rho}{D_u^2 - D_t^2} \right)^{1/2} D_u D_t$$

- The relative error in Q is 1.4% too high.
- Why?
- Answer: *It's a 1-D modeling error!*

Potential Flow – 3

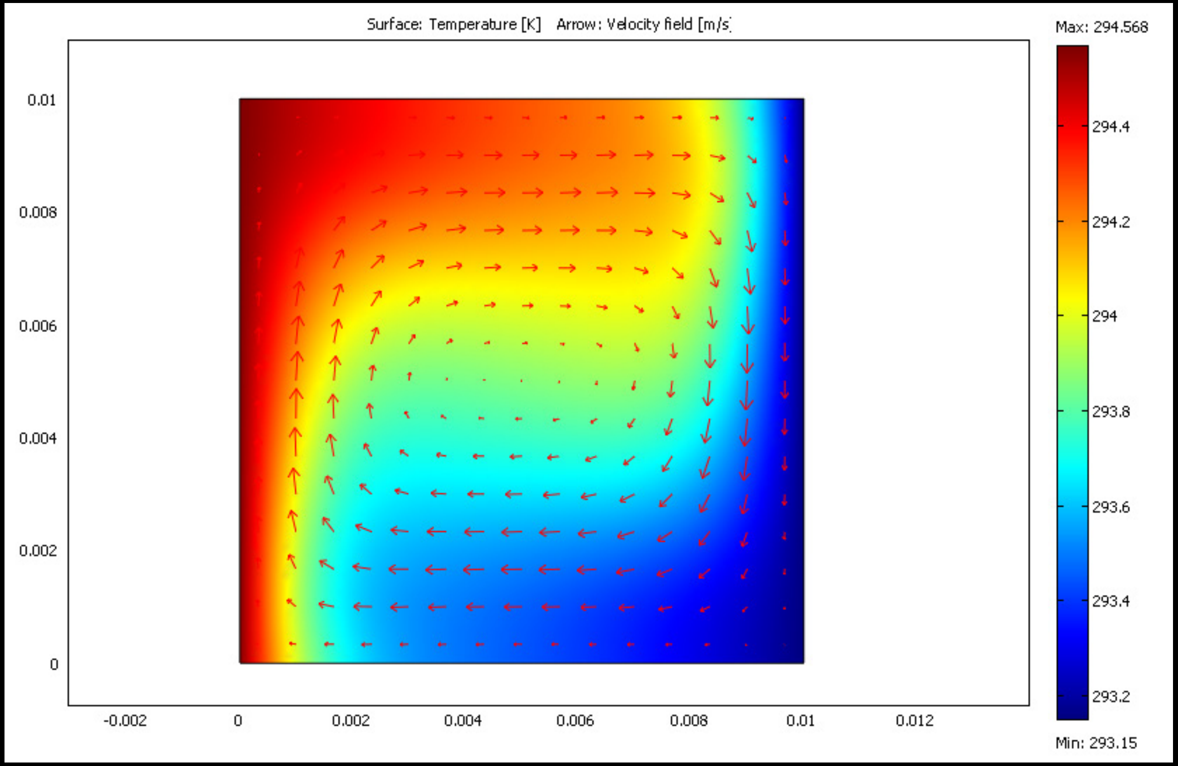
- Why? — The flow is not one-dimensional.



Horizontal velocity at throat

Thermal Convection

- Side heating: Boussinesq approximation and temperature-dependent properties.



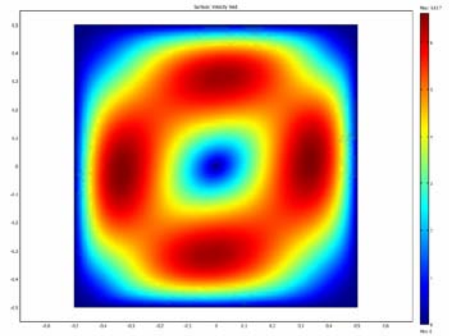
Color: temperature, Arrows: velocity

Thermal Convection – 2

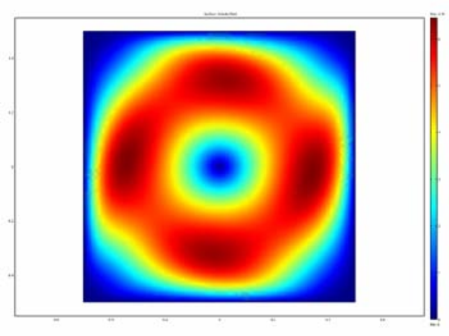
- Effect of Prandtl number

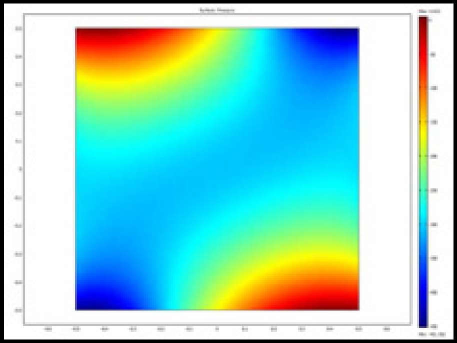
$Ra = 2000, \quad Pr = 7$

$Ra = 2000, \quad Pr = 0.1$

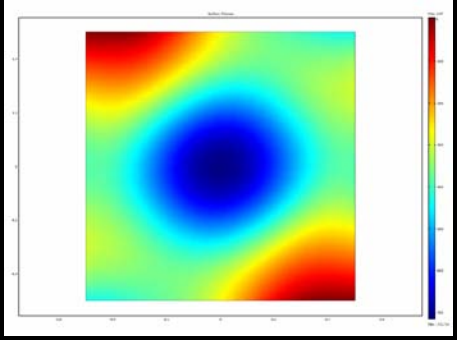


Velocity magnitude





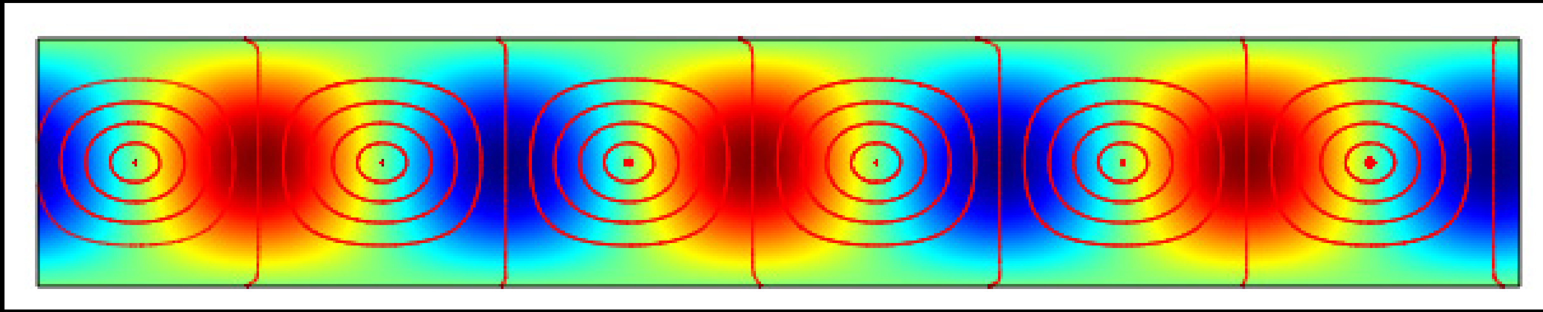
Pressure



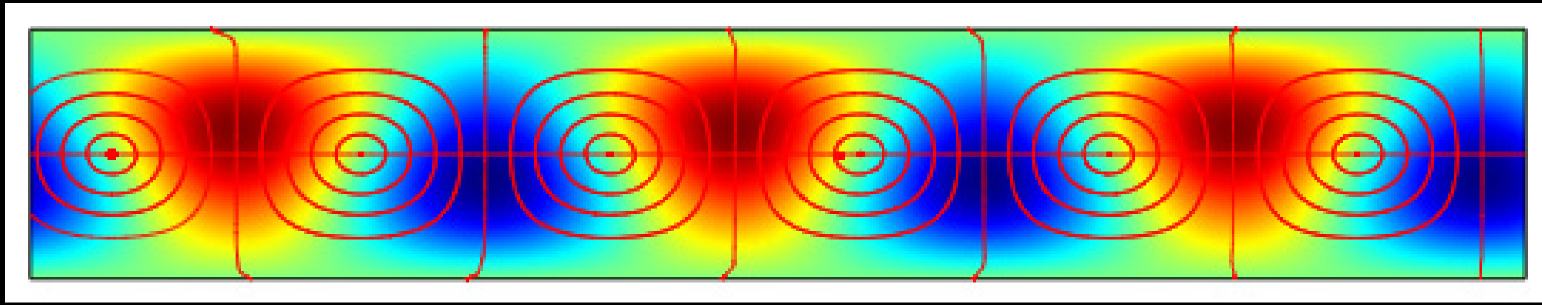
Thermal Convection – 3

- Liquid layer heated from below.

$Ra = 1709$



$Ra = 2000$



Color: temperature,   Streamlines: velocity

Conclusions

- Students: Learned to investigate, interpret, and understand fluid flows. They became very competent with COMSOL.
- Professor: Lots of work, lots of fun.
- Needs: Better or easier tools.
  - Solution quality: element quality, residuals, global mass, force, and energy balances.
  - Particle-tracing tool.
  - Projected streamlines in a plane for 3-D flows.