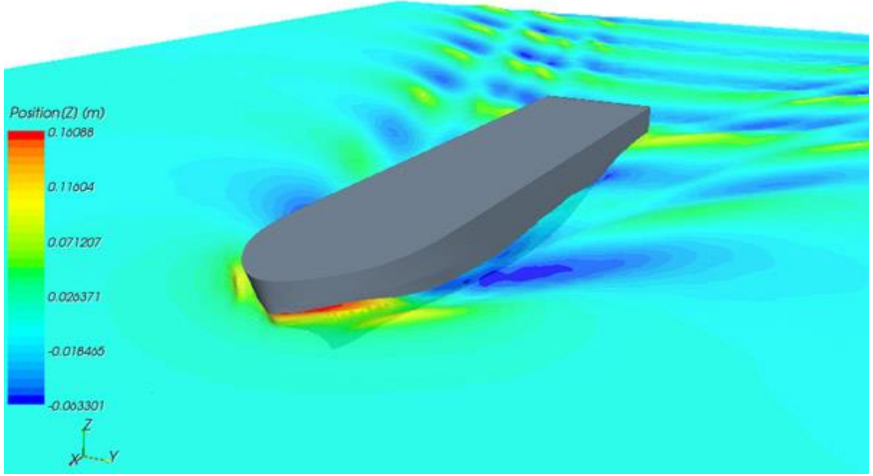
Applied Computational Fluid Dynamics

in Marine Engineering



Norwegian University of Science and Technology

Objectives

- Understand basic CFD theory
- Learn how to set up and run simulations in Star CCM+ and interpret results
- Learn about limitations and important factors to achieve accurate and stable calculations

Topics during the semester

1. Introduction to CFD and fluid mechanics
2. Governing equations in fluid flow
3. Discretization and solution methods
4. Meshing
5. Unsteady problems
6. Free-surface modeling
7. Turbulence and its modeling – the RANS equations

Recommended Literature

Lecture Notes by V. Krasilnikov (Fronter)

Star CCM+ Guidelines

Best Practice Guidelines for Marine Applications of CFD (Fronter)

Other:

Any book about fundamentals in Fluid Mechanics (example Frank White)

Before we start…

- Practical info about the course found on Blackboard
  - Course plan
  - Thursdays 12.15-16.00 in C215 / Fridays 8.15-12.00 in F414
  - Assignments and deadlines
  - Project

- Test Star CCM+ with vmware
- License key on Blackboard
- Login into the Steve Portal, e-learning (check if all can log in)
- Exam info
- List of students

Teaching methods and material

- PowerPoint slides and blackboard
- Relevant examples in class (hand-written + Star CCM+)
- Main assignments every week.
  - Relevant example given on forehand
  - Walkthrough after hand-in

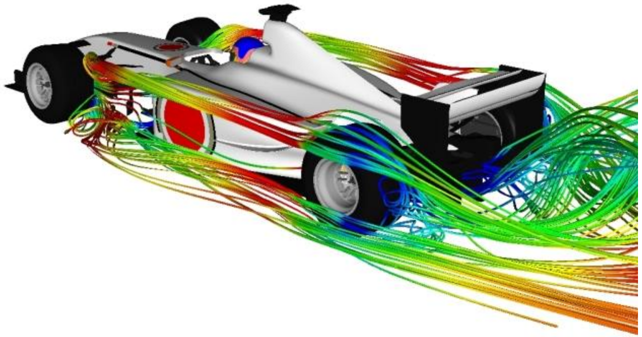
Today

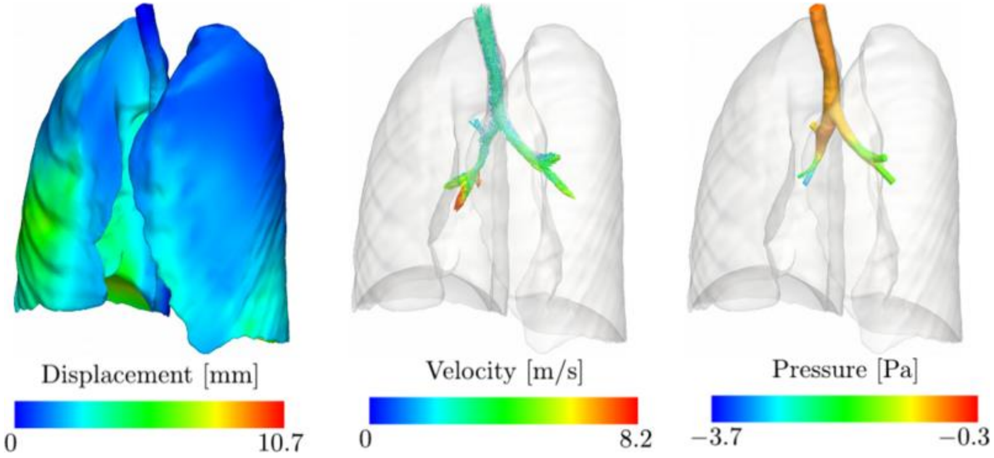
1. What is CFD, why is it needed and how is it used?
2. Examples
3. Hands-on example (filling of bucket)
4. Historical perspectives
5. Workflow in a CFD software
6. Some theory
7. Working example in Star CCM+

Recommended reading: page 1-19 in Lecture Notes by *Krasilnikov*

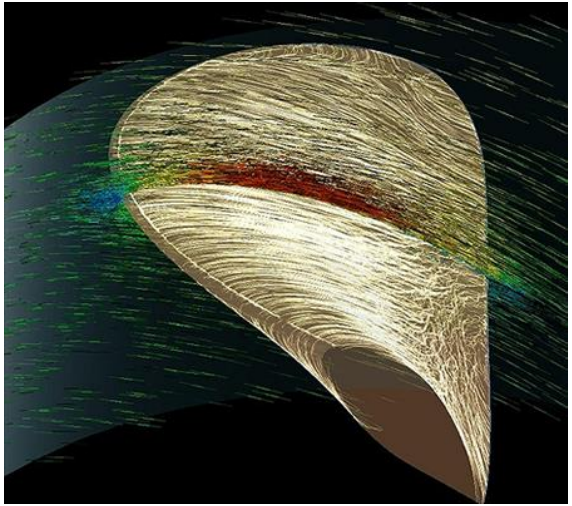
1.1 What is CFD …

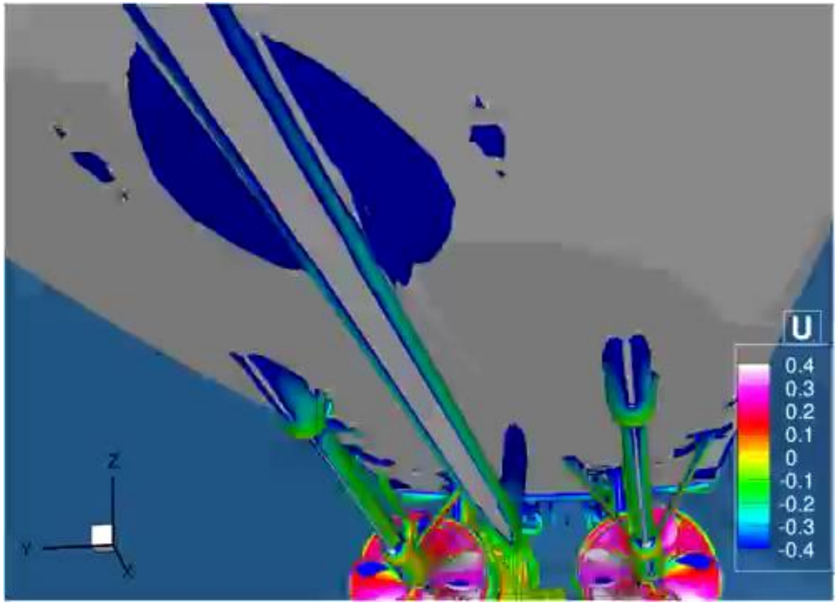
Systems that involves fluid flow, heat transfer, chemical reactions and more are analyzed by means of computer-based simulations

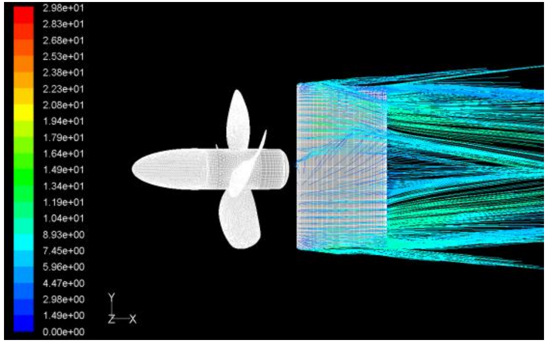


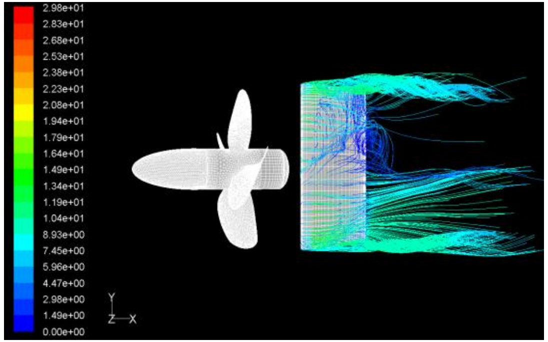


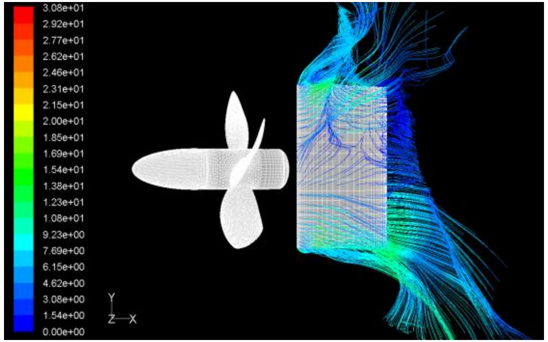
NTNU



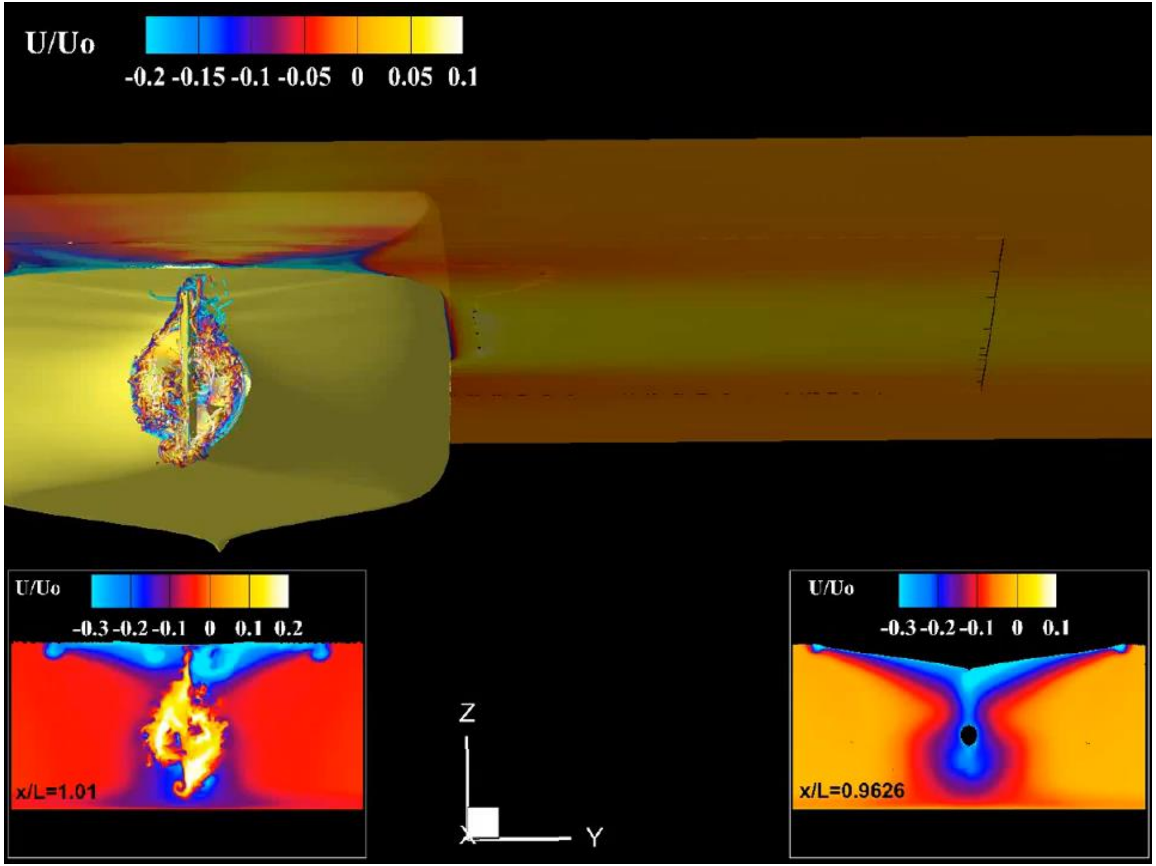

U
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Z
Y
X


2.98e+01
2.83e+01
2.68e+01
2.53e+01
2.38e+01
2.23e+01
2.08e+01
1.94e+01
1.79e+01
1.64e+01
1.49e+01
1.34e+01
1.19e+01
1.04e+01
8.93e+00
7.45e+00
5.96e+00
4.47e+00
2.98e+00
1.49e+00
0.00e+00


2.98e+01
2.83e+01
2.68e+01
2.53e+01
2.38e+01
2.23e+01
2.08e+01
1.94e+01
1.79e+01
1.64e+01
1.49e+01
1.34e+01
1.19e+01
1.04e+01
8.93e+00
7.45e+00
5.96e+00
4.47e+00
2.98e+00
1.49e+00
0.00e+00


3.08e+01
2.92e+01
2.77e+01
2.62e+01
2.46e+01
2.31e+01
2.15e+01
2.00e+01
1.85e+01
1.69e+01
1.54e+01
1.38e+01
1.23e+01
1.08e+01
9.23e+00
7.69e+00
6.15e+00
4.62e+00
3.08e+00
1.54e+00
0.00e+00

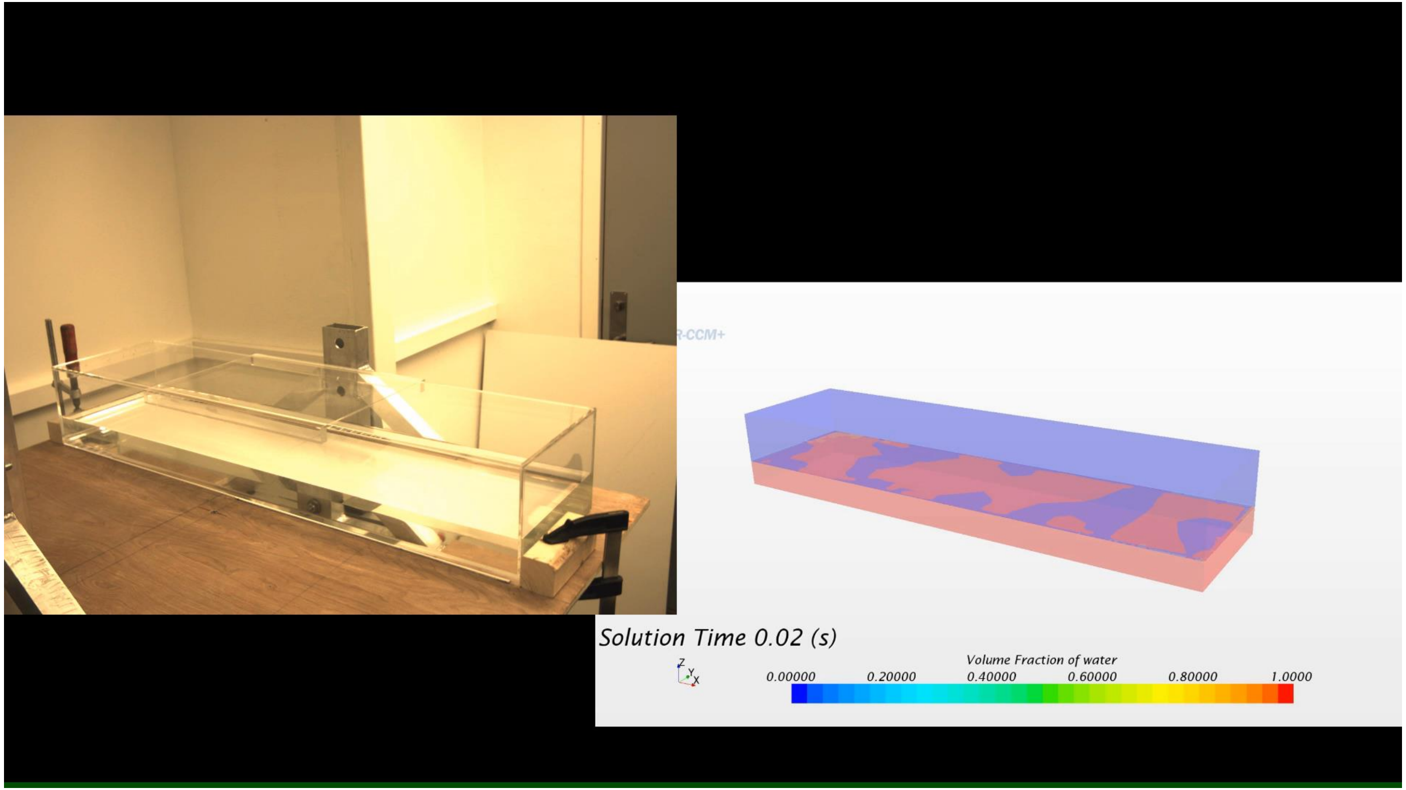
NTNU



U/Uo
-0.2 -0.15 -0.1 -0.05 0 0.05 0.1
U/Uo
-0.3 -0.2 -0.1 0 0.1 0.2
x/L=1.01
Z
Y
X
U/Uo
-0.3 -0.2 -0.1 0 0.1
x/L=0.9626

NTNU

More examples - *sloshing*



But is it just nice contour plots?

Diff. equations that describes the physical behaviour of a fluid can not be solved analytically other than for simple cases.

The governing equations are discretized and represented as a system of linear or non-linear algebraic equations.

This system of equations must be solved

NTNU

Abbreviation

Computational + Fluid + Dynamics

Calculation or computation like in mathematics, physics or economy

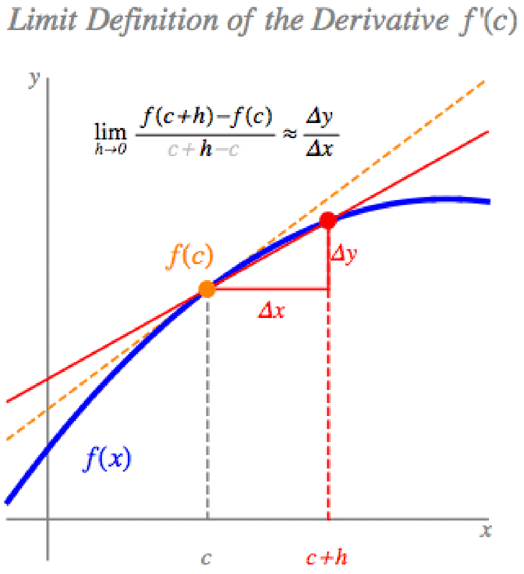
A continuum of liquid or gas
A continuous substance

Variation of a state
Something changing in time and/or space

Approximate solution of the derivative

Definition derivative of function $f = f(x)$:

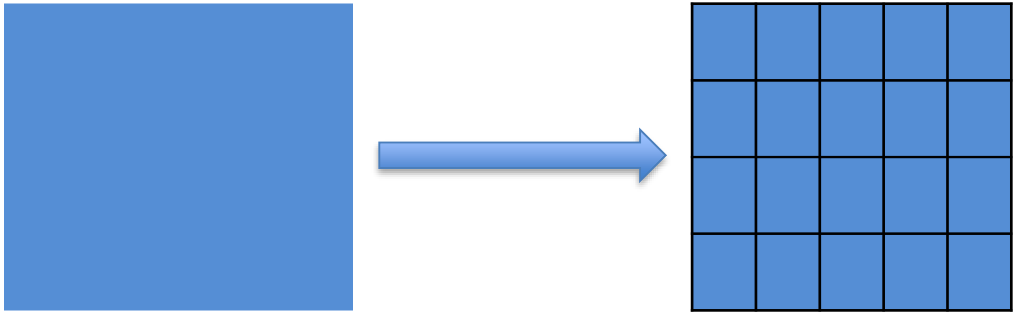
$$\left(\frac{\partial f}{\partial x}\right)_{x_i} = \lim_{\Delta x \to 0} \frac{f(x_i + \Delta x) - f(x_i)}{\Delta x}$$

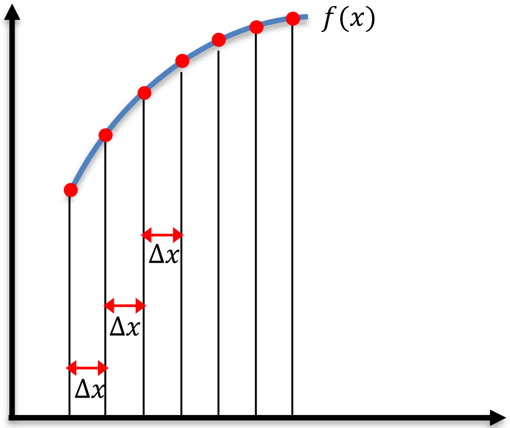


Derivative vs. Numerical

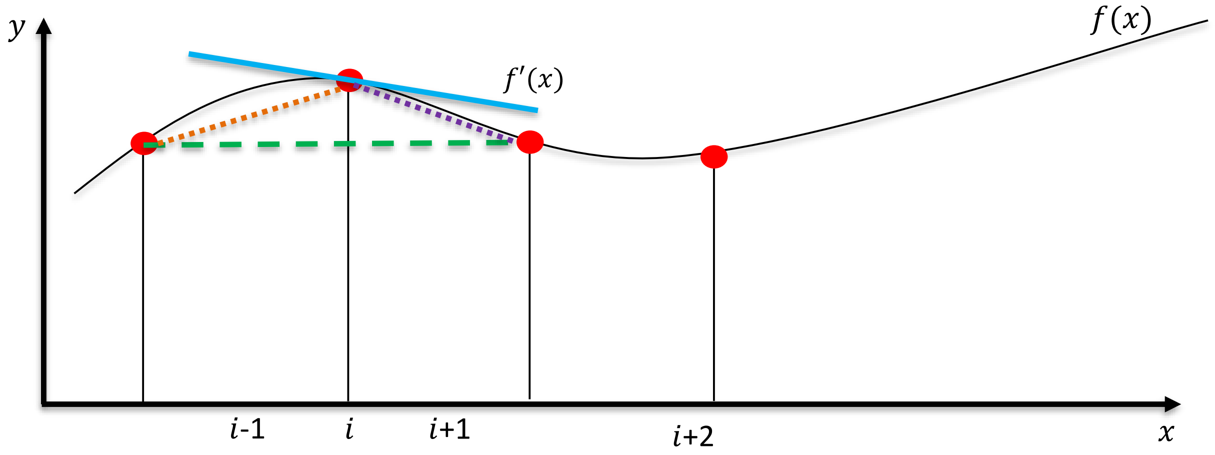
Definition derivative of function $f = f(x)$:

$$\left(\frac{\partial f}{\partial x}\right)_{x_i} = \lim_{\Delta x \to 0} \frac{f(x_i + \Delta x) - f(x_i)}{\Delta x}$$





First Derivative



Forward difference: $f'(x_i) \approx \frac{f(x_{i+1})-f(x_i)}{x_{i+1}-x_i} = \frac{y_{i+1}-y_i}{x_{i+1}-x_i}$

Backward difference: $f'(x_i) \approx \frac{f(x_i)-f(x_{i-1})}{x_i-x_{i-1}} = \frac{y_i-y_{i-1}}{x_i-x_{i-1}}$

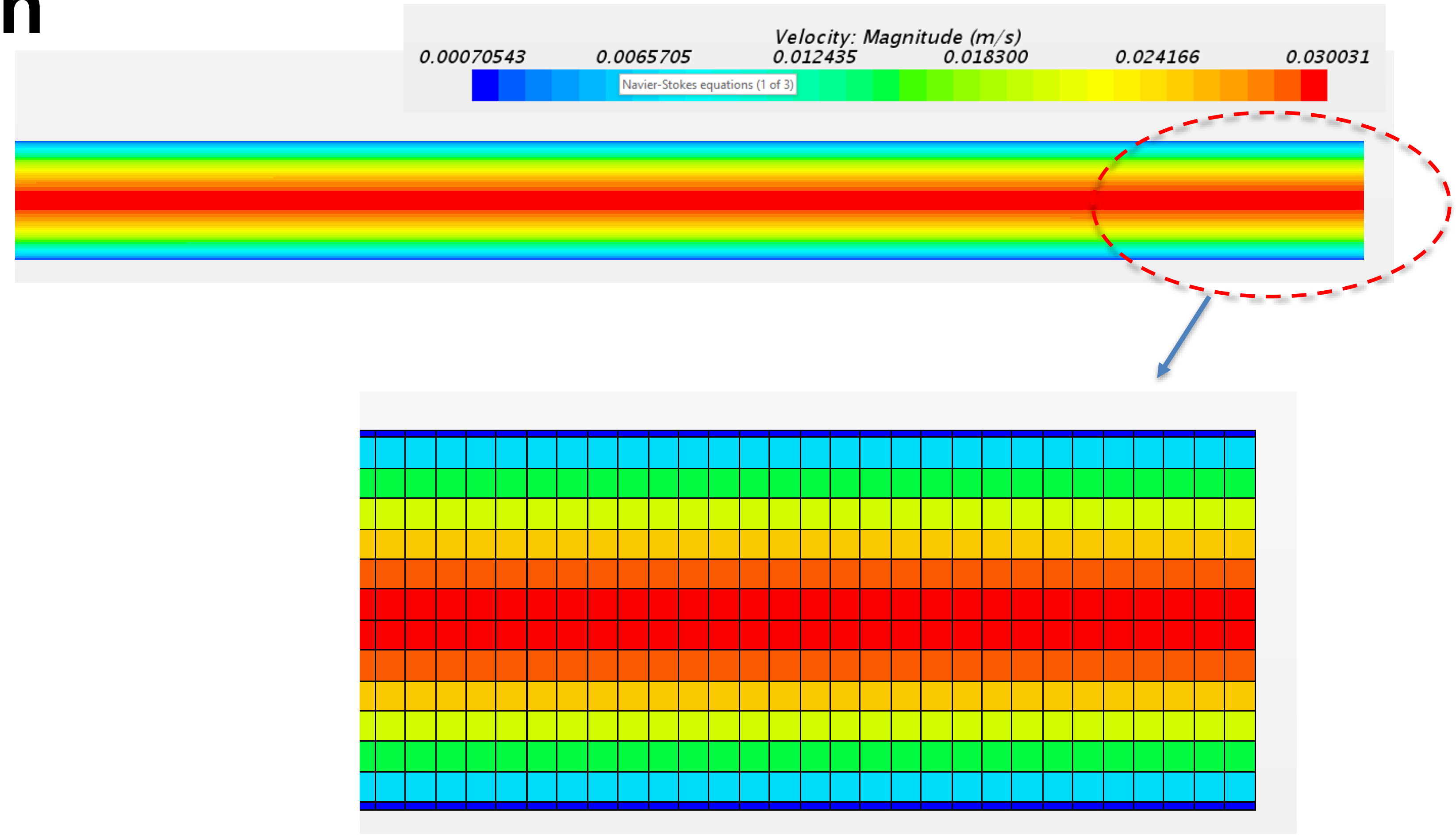
Central difference: $f'(x_i) \approx \frac{f(x_{i+1})-f(x_{i-1})}{x_{i+1}-x_{i-1}} = \frac{y_{i+1}-y_{i-1}}{x_{i+1}-x_{i-1}}$

Navier-Stokes equations (1 of 3)

$$\frac{\partial u}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho vu)}{\partial y}+\frac{\partial(\rho wu)}{\partial z}$$

$$=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(-\frac{2}{3}\mu\nabla\cdot\boldsymbol{U}+2\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right]+\rho f_x$$

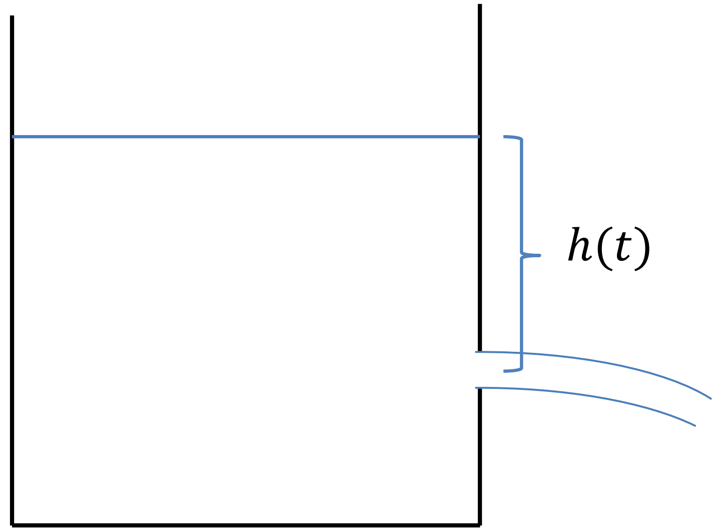
Mesh



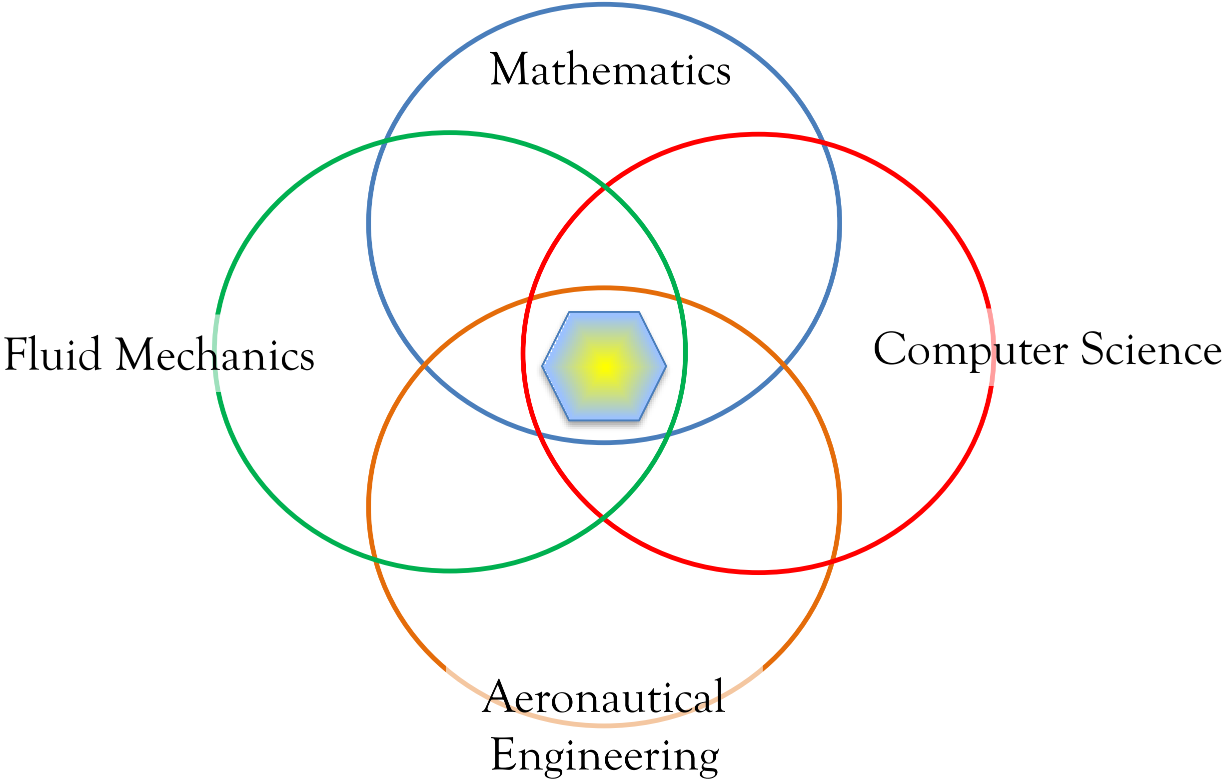
Velocity: Magnitude (m/s)
0.00070543
0.0065705
0.012435
0.018300
0.024166
0.030031
Navier-Stokes equations (1 of 3)

Simple example – *a bucket with a hole*

- Set up a diff equation for the height level *h(t)*
- Solve numerically and compare with analytic → $\Delta t = \left(1 - \frac{1}{\sqrt{2}}\right)\frac{A_1}{A_2}\sqrt{\frac{2h_0}{g}}$
- Use the Torricelis formula, $V_e \approx \sqrt{2gh(t)}$
- Approximate $\frac{dh}{dt}$ with backward Euler
- ss



Multi-Disciplinary Nature of CFD



Historical perspectives – 20th century

1850-19xx

Reynolds (experiments, transition), Prandtl – boundary layer theory, mixing length, Taylor, Kolmogorov
Navier-Stokes equations

1930's

Early numerical simulation of flow past cylinder at low speeds

1960's

Los Alamos, Marker-and-Cell, Arbitrary Lagrangian-Eulerian (ALE), turbulence modeling
Birth of the super-computer CDC6600 (3 Megaflops)

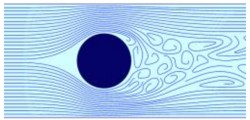
1970's

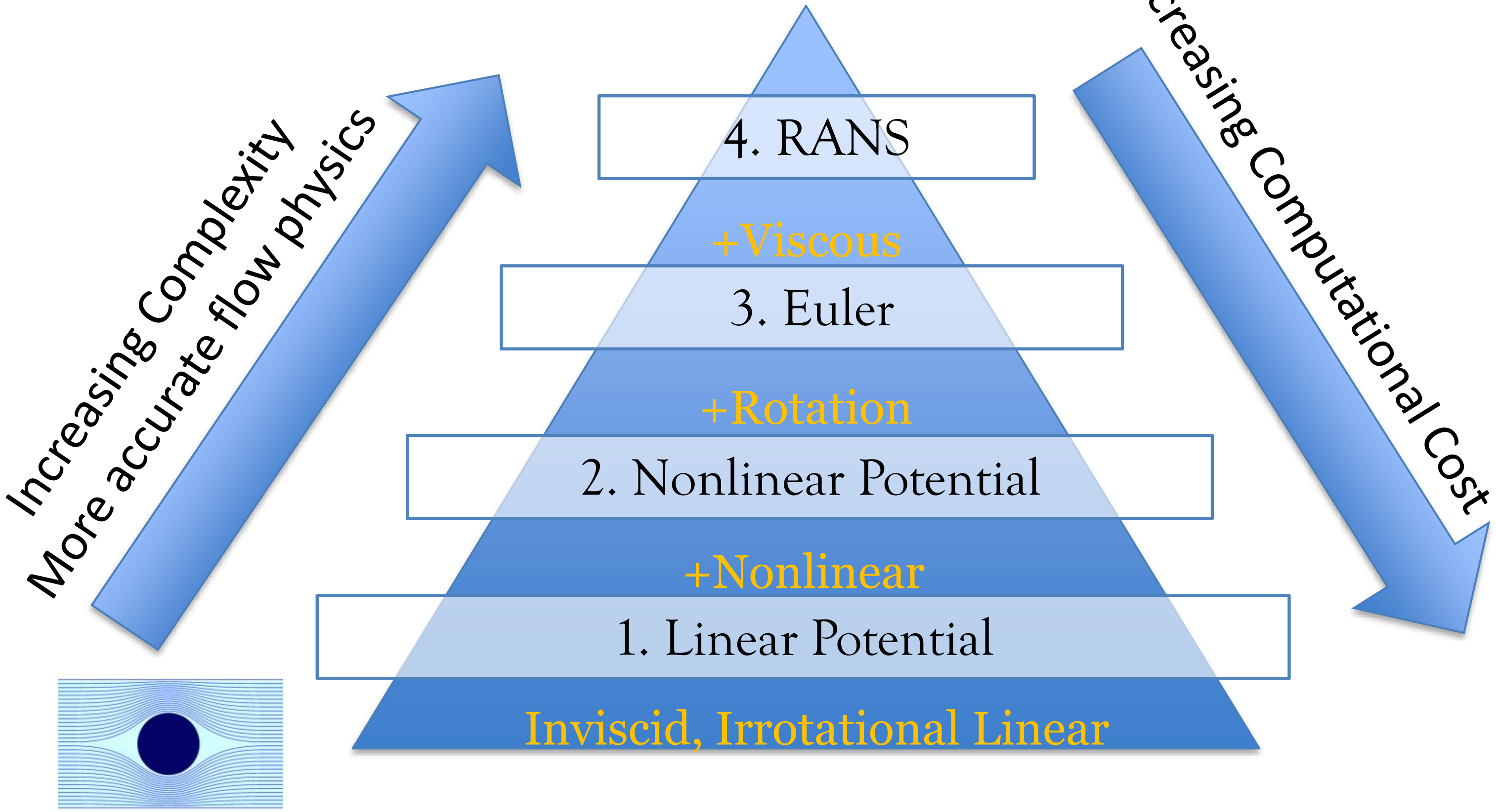
Spalding (Imperial College London), SIMPLE, k-eps, eddy break-up

1980's

Finite Volume method, Patankar's book

Accuracy and cost





Advantages of CFD (vs. Experiments)

CFD	Experiments
Low cost	Costly
Pre-proc. Solving	Preparation, Execution
Complete information	Limited information
Control of model	Controlling experiments
Model unchanged	Repeatability/statistics
At any scale	Scaled
Accuracy of numerical model	Accuracy of instruments

Non-dimensional numbers in fluid dyn.

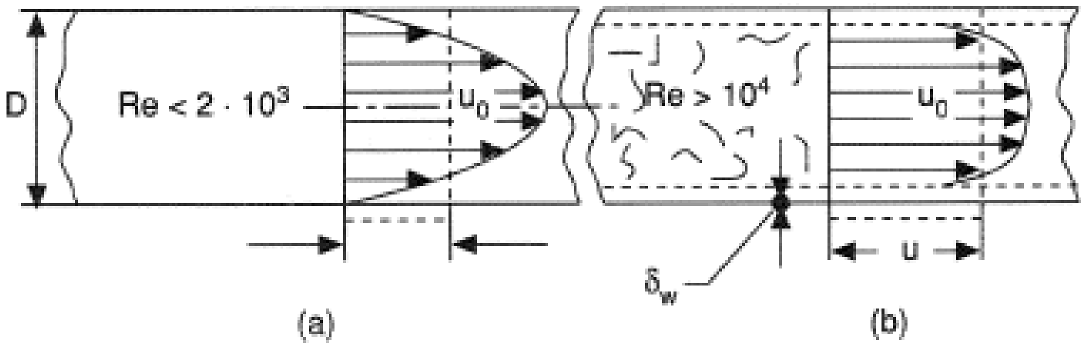
Name	Definition	Meaning
Reynolds number	$Re = \frac{\rho \mathrm{UL}}{\mu}$	Ratio of inertial and viscous forces
Froude number	$Fr = \frac{\mathrm{U}}{\sqrt{g \cdot L}}$	Ratio of inertial and gravitational forces
Strouhal number	$St = \frac{fL}{U}$	Ration of unsteady velocity to ambient velocity
Euler number	$Eu = \frac{\Delta P}{\rho V^2}$	Ratio of stream pressure and inertia

Non-dimensional coefficients

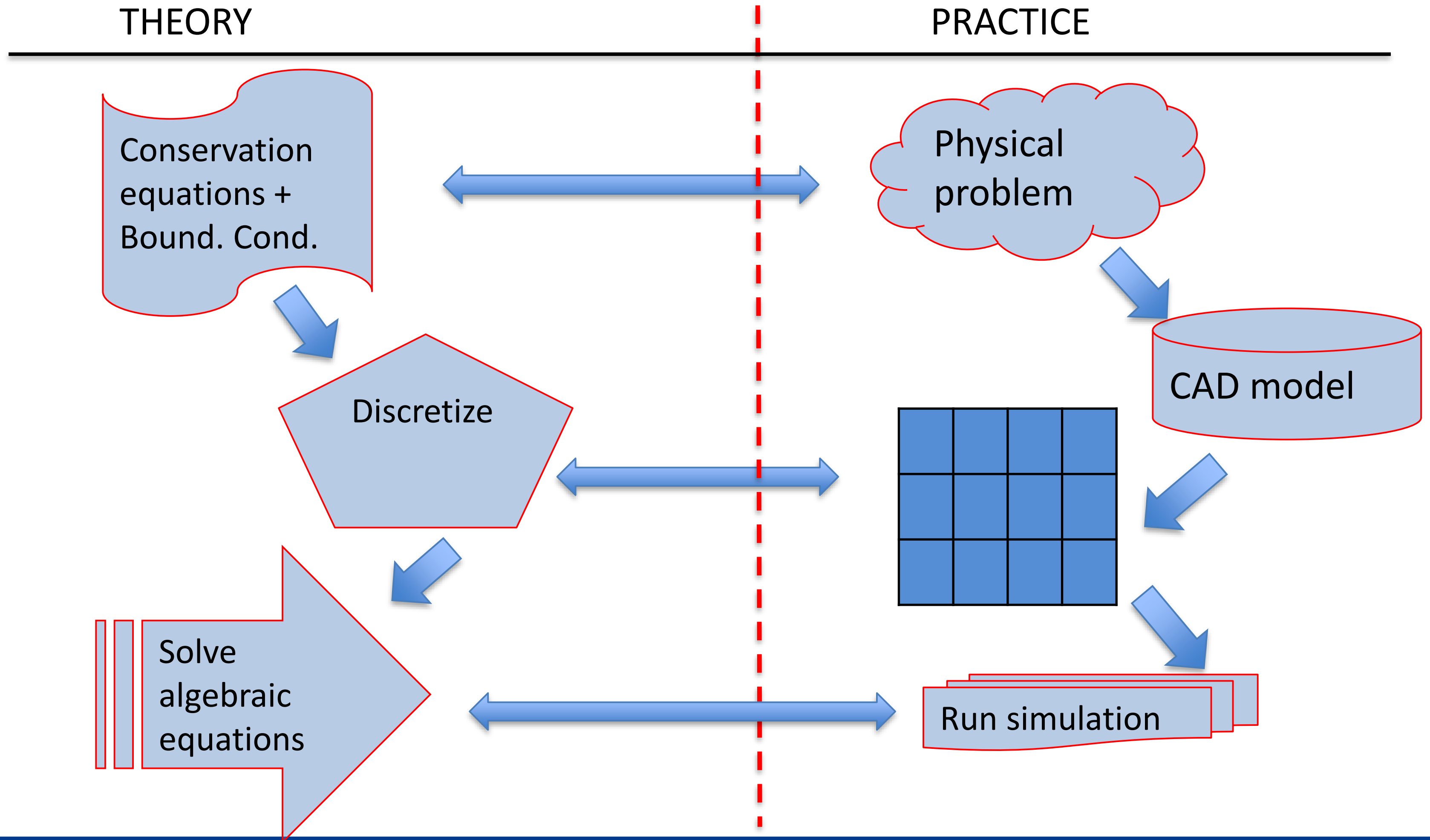
Name	Definition	Meaning
Force coefficient (or drag)	$C_F = \frac{F}{\rho A U^2/2}$	
Moment coefficient	$C_M = \frac{M}{\rho z A U^2/2}$	
Pressure coefficient	$C_p = \frac{p - p_\infty}{\rho U^2/2}$	

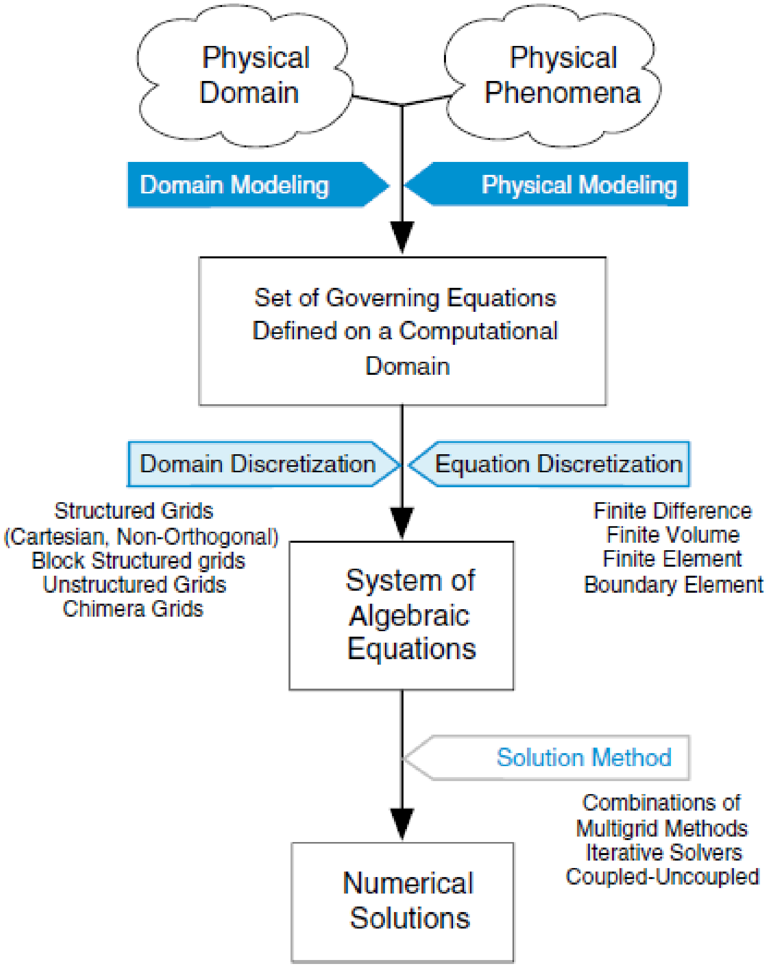
Example use of non-dim. number

- Internal flow in a pipe



NTNU


THEORY
PRACTICE
Conservation equations + Bound. Cond.
Physical problem
CAD model
Discretize
Solve algebraic equations
Run simulation



How is it done in theory?

From: “*The Finite Volume Method in Computational Fluid Dynamics*” – Moukalled et al.

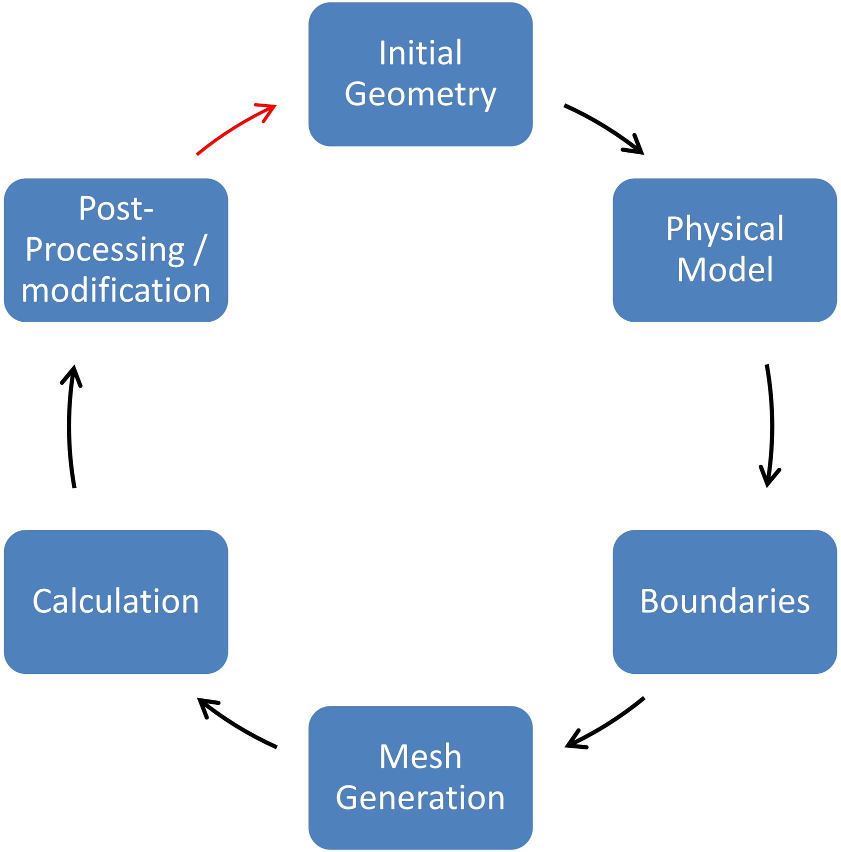
How is it done in practice?

1. Pre-processing

2. Solving

3. Post-processing

CFD workflow



NTNU

Preprocessing

1. Define the solution domain
2. Prepare the necessary CAD model
3. Define the regions: Fluid, solid or mixture
4. Define boundary- and initial conditions
5. Meshing (numerical grid)
6. Select physical models
7. Operating conditions
8. Solver controls
9. Monitors

Solving

- The discretized conservation equations are solved directly or iteratively. A number of iterations are usually required to reach a converged solution.

- Convergence is reached when:
  - ✓ Changes in solution variables from one iteration to the next are negligible
  - ✓ Residuals provide a mechanism to help monitor this trend
  - ✓ Overall property of conservation is achieved

- The accuracy of a converged solution is dependent upon:
  - ✓ Appropriateness and accuracy of the physical models.
  - ✓ Grid resolution and independence
  - ✓ Problem setup

Post-processing

- Various types of visualization can be used to examine the qualitative results. E.g. look for overall flow pattern, any separation, vortex formation and so on
  - ✓ Velocity vectors
  - ✓ Pathline and particle trajectory plots
  - ✓ Velocity or pressure magnitudes (contour plots)
  - ✓ XY-plots
  - ✓ Animations
- Numerical reporting tools can be used to examine the quantitative results
  - ✓ Flux balance
  - ✓ Surface and volume integrals
  - ✓ Forces and moments (including non-dimensional coefficients)

Good advice

Before you start working on the model, try to collect as much information as you can about the problem.

The better you can predict the physical behavior of the actual case, the better is your chance to make a realistic model