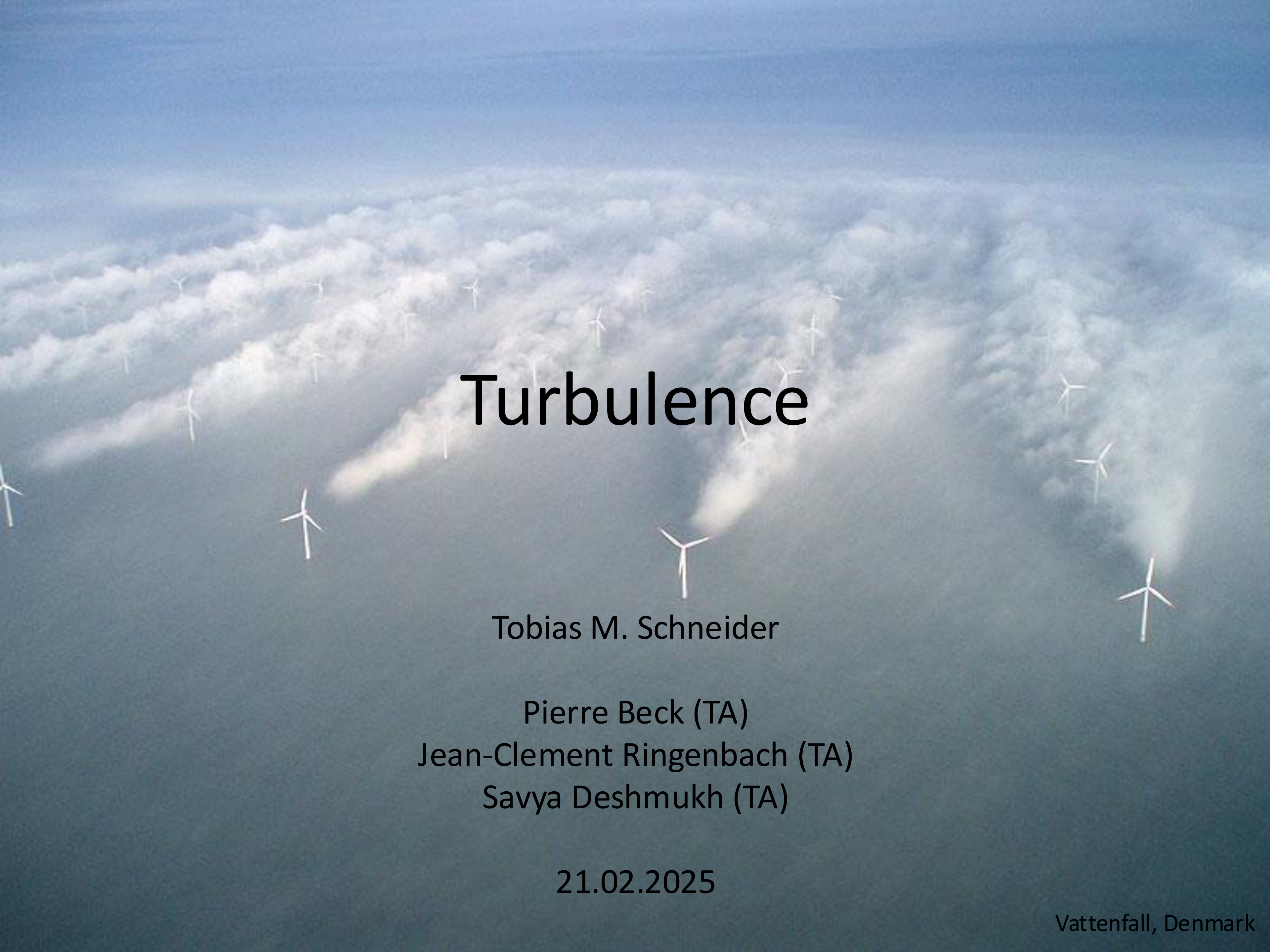

Turbulence

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Savya Deshmukh (TA)

21.02.2025

Vattenfall, Denmark

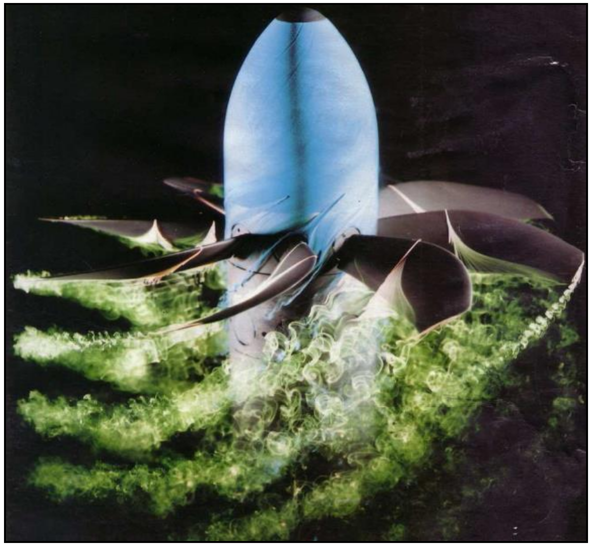
Plan for today

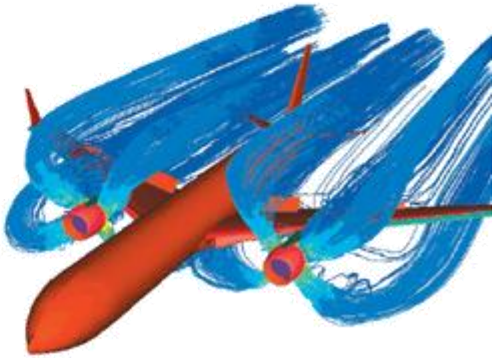
1. **Introduction**
   - **What is turbulence?**
   - **Plan for the class**

2. **Practical issues**
   - **Literature**
   - **Exercises**
   - **How to get help?**
   - **…..**

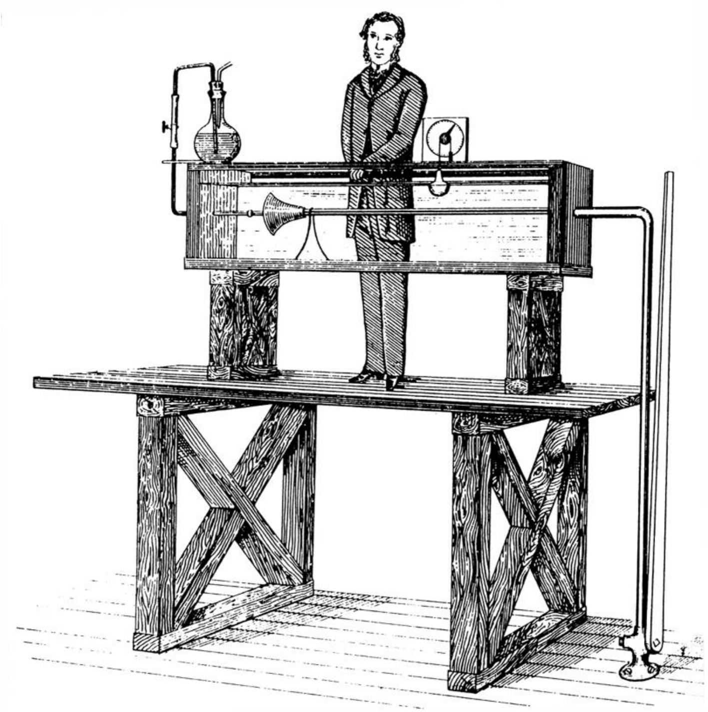
3. **Let's get started……**

Turbulent flows





Pipe turbulence (Reynolds 1883)



Observations:
- turbulence is unsteady and chaotic
- characterized by swirls and vortices
- enhanced mixing
- enhanced dissipation and drag

Turbulence - ‚*the most important unsolved problem of classical physics*' (Feynman)

Equations for (incompressible) turbulence
(Navier 1823)

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \mu\nabla^2\mathbf{v} + \mathbf{f}.$$
$$\nabla\cdot\mathbf{v} = 0.$$

"Equation of life" (?) (Feynman 1964)
Schrödinger equation

$$i\hbar\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

Question: Where is biology / turbulence in these equations?

Answer requires: Detailed observations, experiments, models,….

(Some) aspects of turbulence research

Modeling (numerical)
- RANS
- LES
- turbulence models

Analytical models
- law of the wall
- mixing length ideas
- scaling of turbulent boundary layers

'Applications'
- mixing efficiency
- combustion
- climate science…

Theory
general features of turbulence deduced from Navier-Stokes and (reasonable) assumptions

Kolmogorov 1941, 1962, ….

Non-equ. statistical physics
- active fluids
- phase transitions…

Pictorial concepts
- Richardson cascade

Simulation (CFD)
- DNS
- approximate models

Course outline and objective

1. Introduction – fully developed turbulence
2. Symmetries and conservation laws
3. Probabilistic description of turbulence
4. Review: Statistical tools and methods

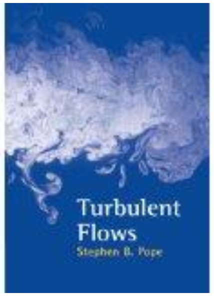
4. Two experimental laws of fully developed turbulence
5. Kolmogorov's 1941 turbulence theory
6. Phenomenology

7. Intermittency – corrections to K41 theory
8. Modeling and simulation: DNS, RANS, LES,….
9. Ergodic Theory and Turbulence

This course provides an introduction to the physical phenomenon of turbulence, its probabilistic description and modeling approaches. ***Thereby students will be equipped with the fundamental understanding of turbulence that allows to tackle specific flow problems in science and engineering practice****.*

Books and practical issues

Books:



Stephen Pope, Cambridge P, 2000

THE reference

Part 1: Fundamentals

Part 2: Modeling and Simulation

Uriel Frisch, Cambridge P, 1995

Focus on theoretical foundations

Used for this class

Moodle:

slides from the class

homework problems & solutions (will not be graded)

recordings from last year

Exercises (Friday 14:15-15:00) – TAs and Tobias Schneider

- First exercise: March 7th

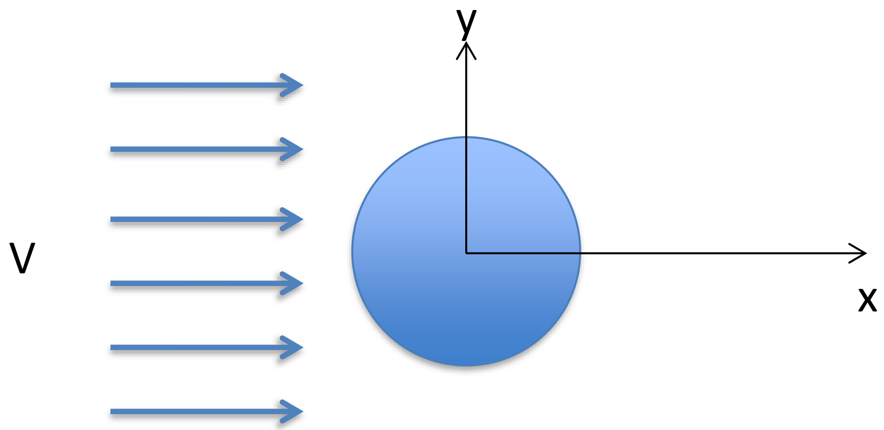
Office hours: Tobias Schneider, Wed. 17h45 – 18h30, MED 2 2826

Grading: - Project exercise (late April & May – dates to be confirmed!!!) (100 %)

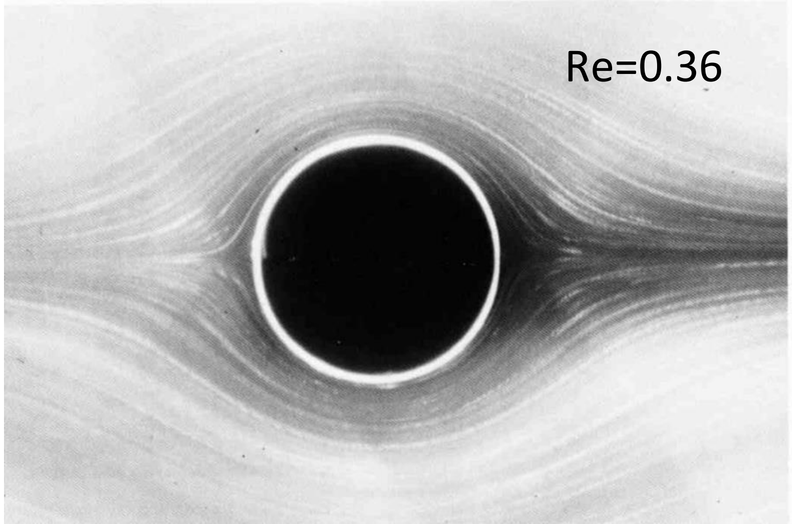
- no additional exam!!

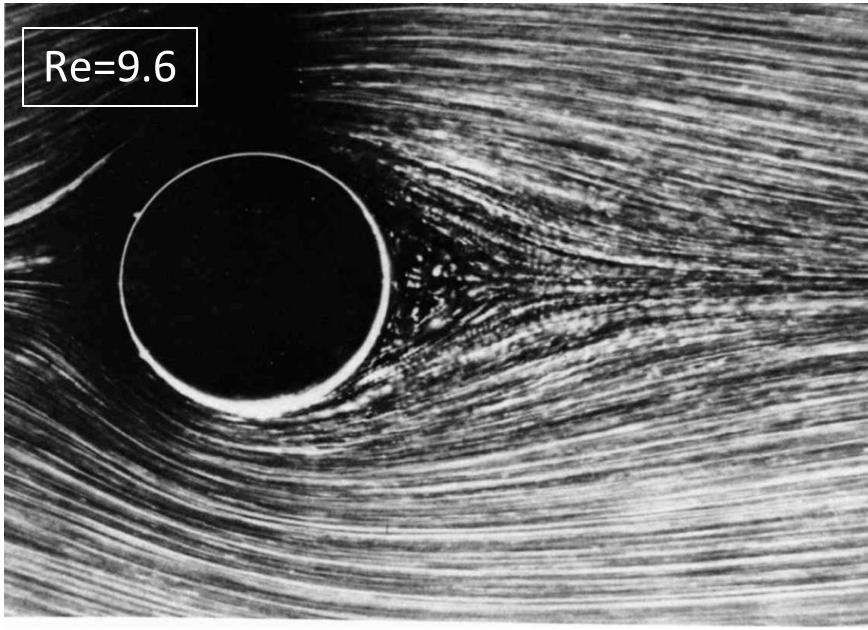
Turbulence and symmetries

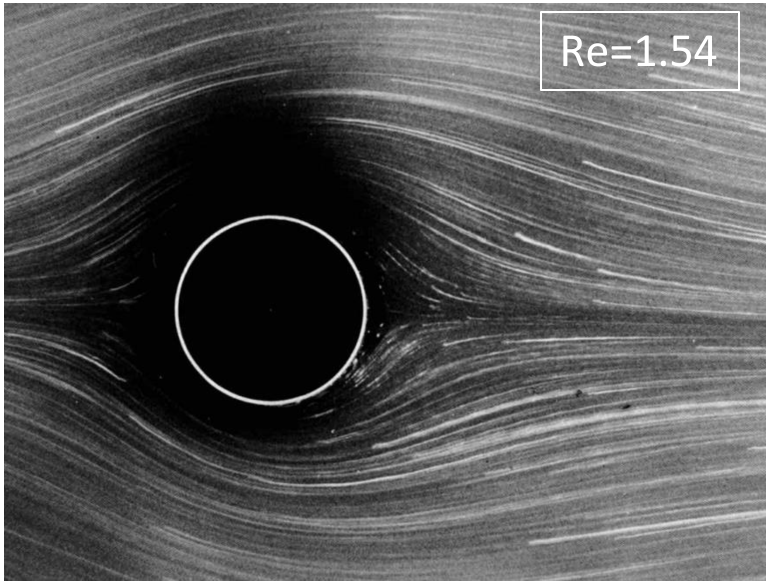
Flow past a cylinder of diameter L

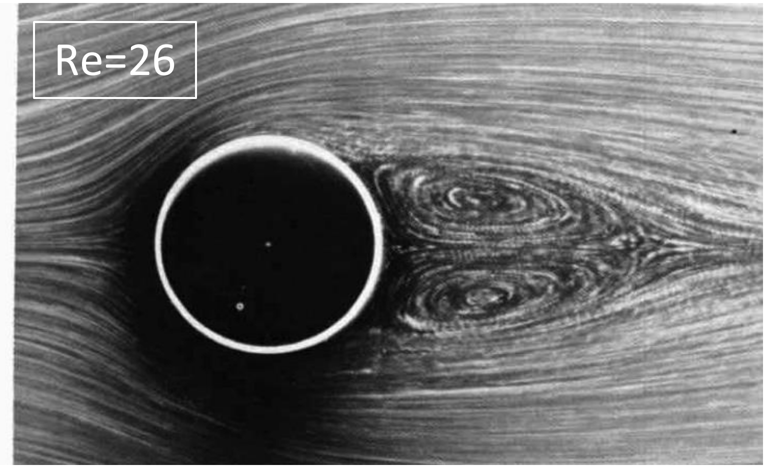


Question: What happens when $Re = VL/\nu$ is increased?

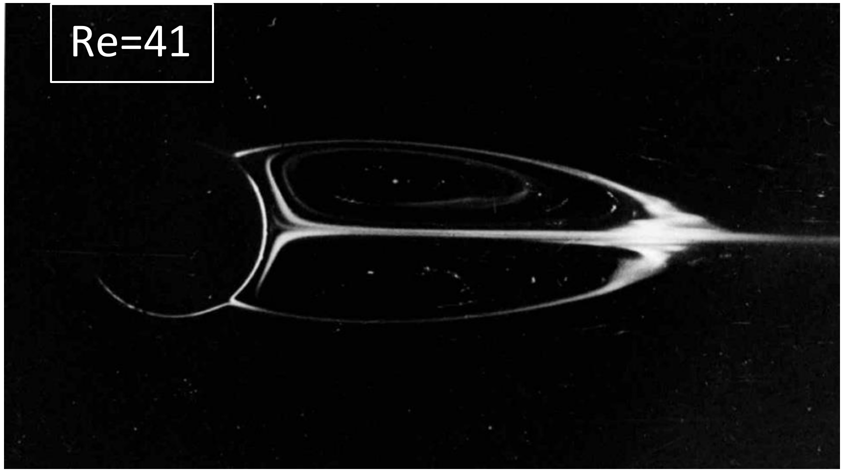


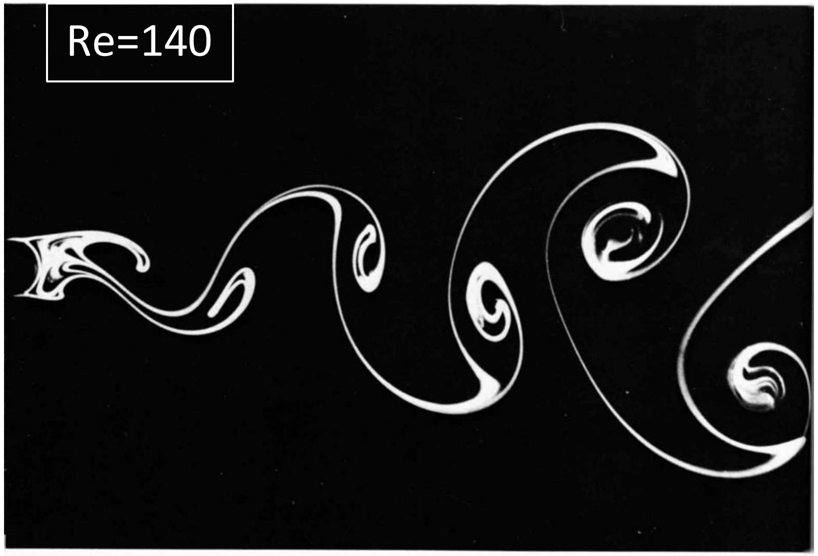


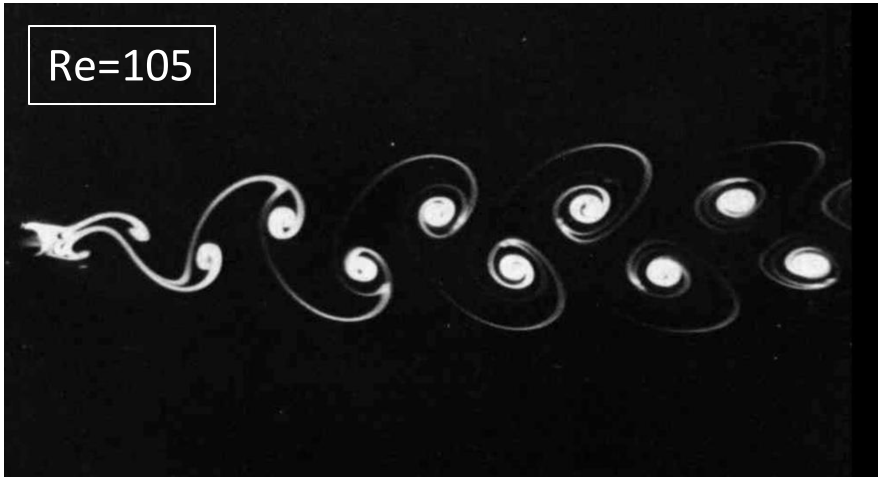


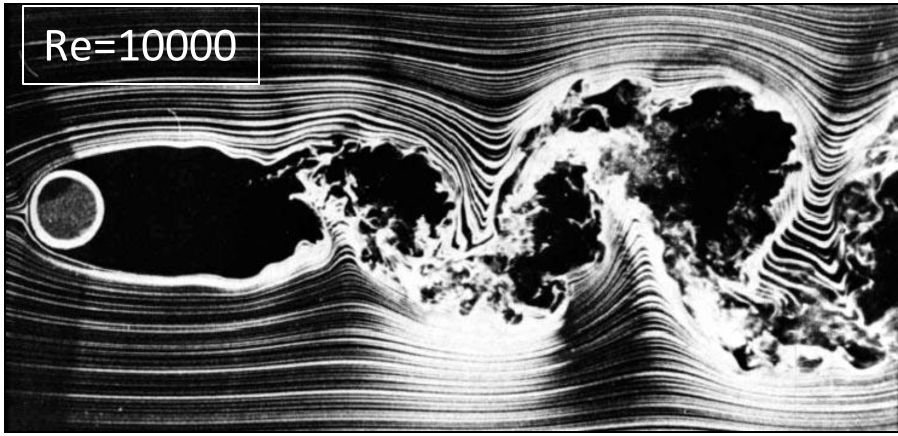


Van Dyke, An Album of Fluid Motion



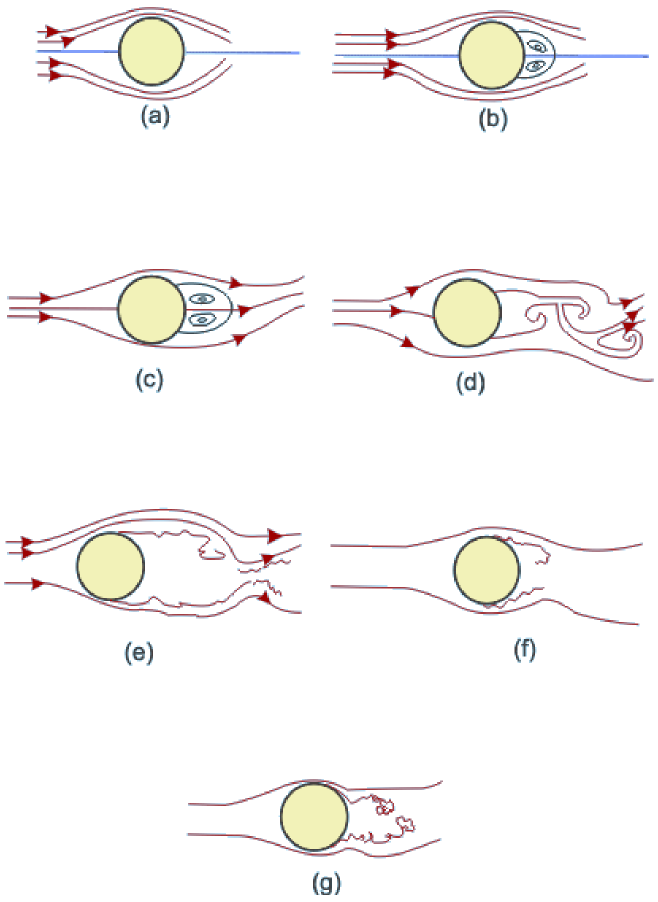






Van Dyke, An Album of Fluid Motion

Schematic

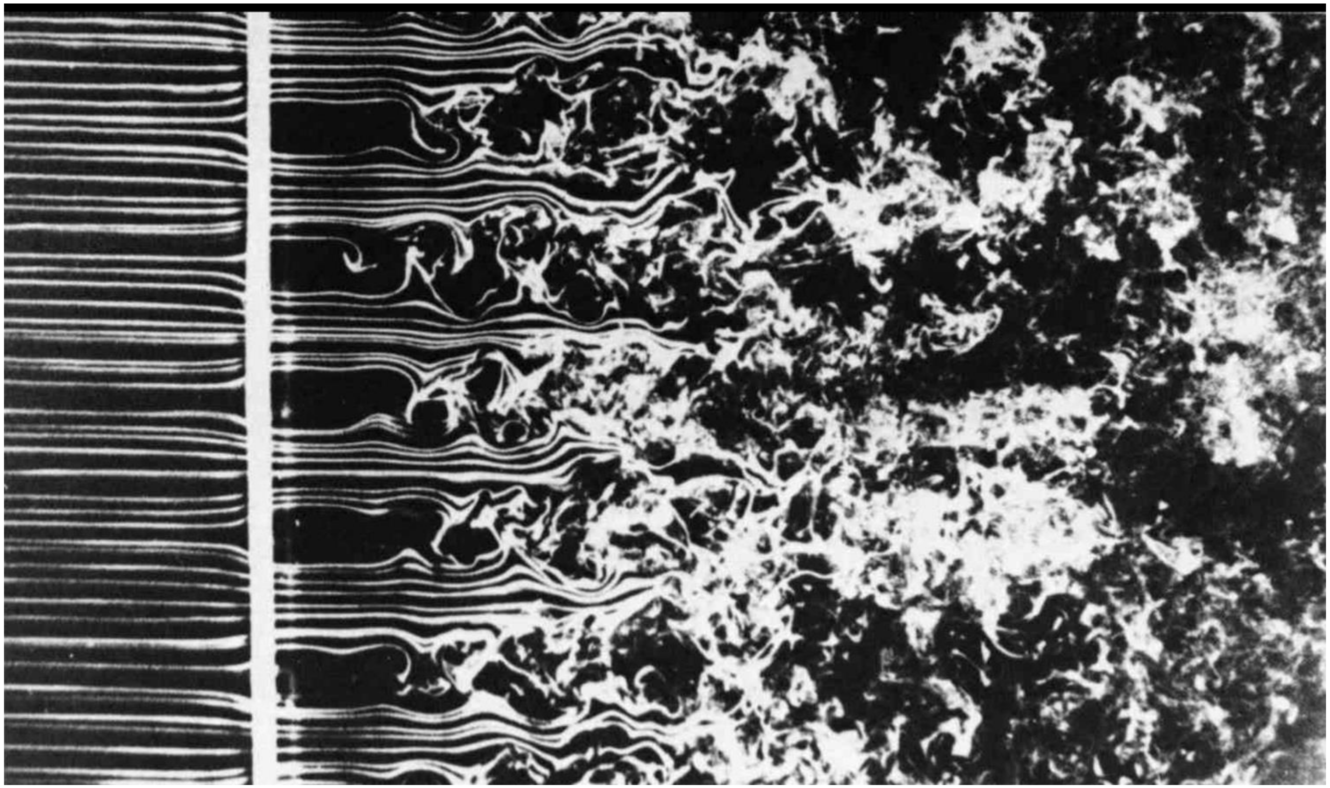


As the Reynolds number increases:

As Re increases, various symmetries permitted by the equations (including boundary conditions) are broken.

At very high Re: Tendency to restore symmetries in a statistical sense and far from boundaries

Flow behind a grid at Re=1500



Homogenous isotropic turbulence (Lord Kelvin 1887)

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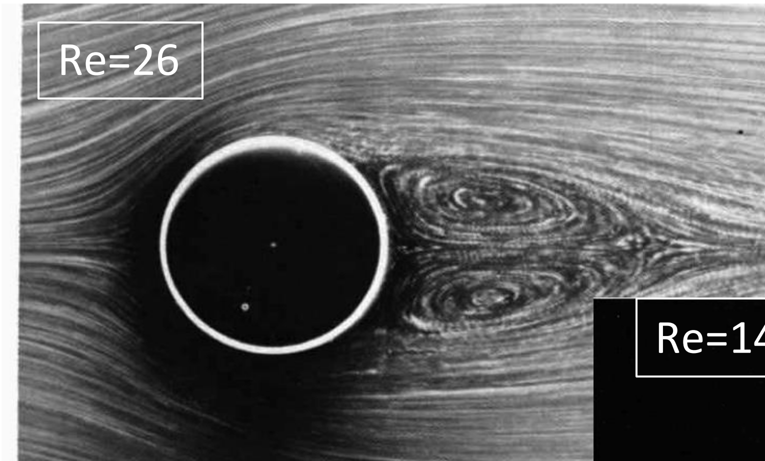
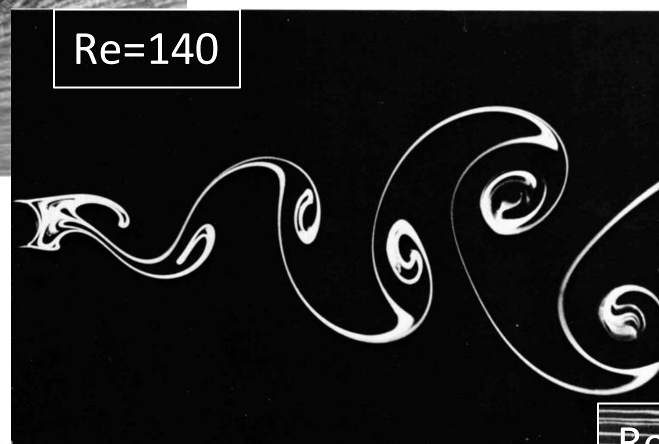
Turbulence and symmetries

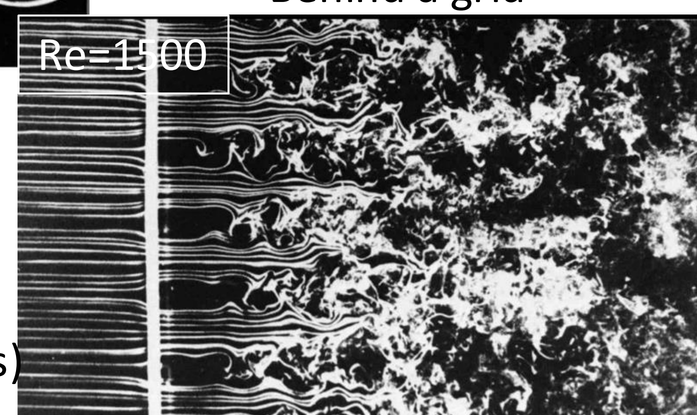


Reynolds number increases



Symmetry breaking

Behind a grid



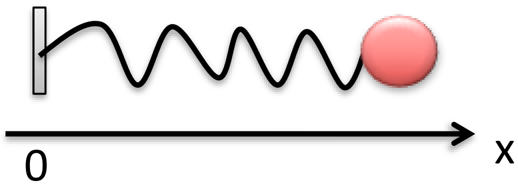
Symmetries recovered
(in a **statistical** sense, far from boundaries)

Fully developed turbulence

Van Dyke, An Album of Fluid Motion

Symmetries of dynamical equations

Example: overdamped particle in a quadratic potential (1D)

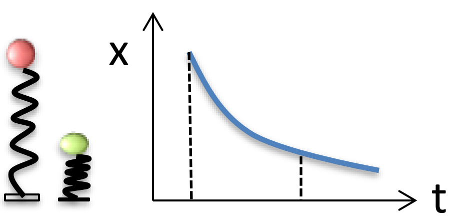


$$\dot{x} = -x; \quad x(t=0) = x_0$$

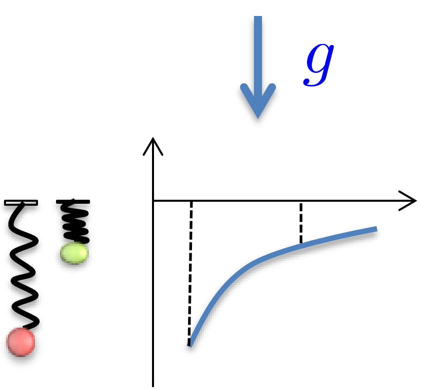
$$x(t) = x_0\, e^{-t} = f^t(x_0)$$

Symmetry: $g: \quad x \to -x$ (reflection)

Transforms solutions into solutions

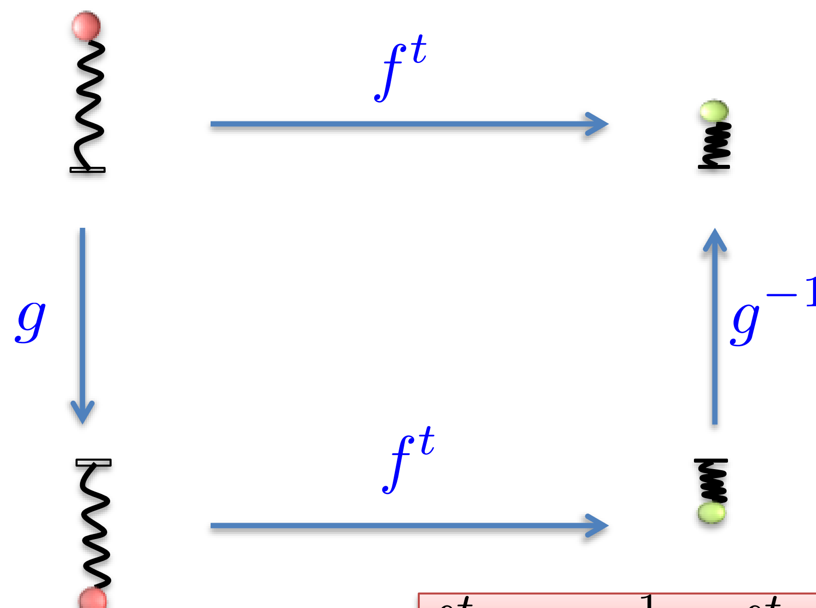


$$x(t) = x_0 e^{-t}$$



$$\hat{x}(t) = \hat{x}_0 e^{-t}$$
$$= (-x_0) e^{-t}$$
$$= -x(t)$$

Symmetry and time evolution commute



$$f^t = g^{-1} \circ f^t \circ g$$