Boulder Summer School on Condensed Matter

Lectures on Transitional Turbulence

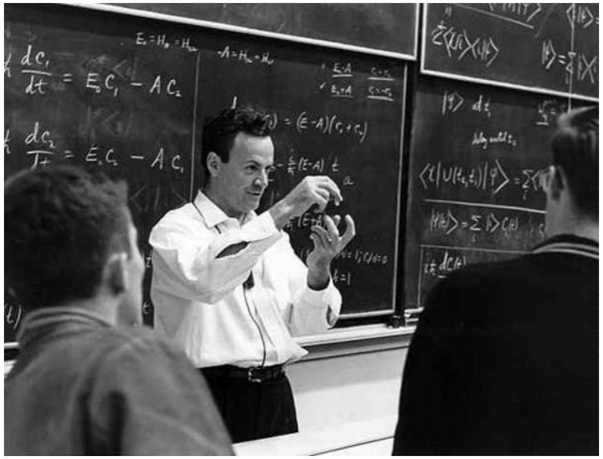
Slides created mainly by NG, plus Hong-Yan Shih & Xueying Wang

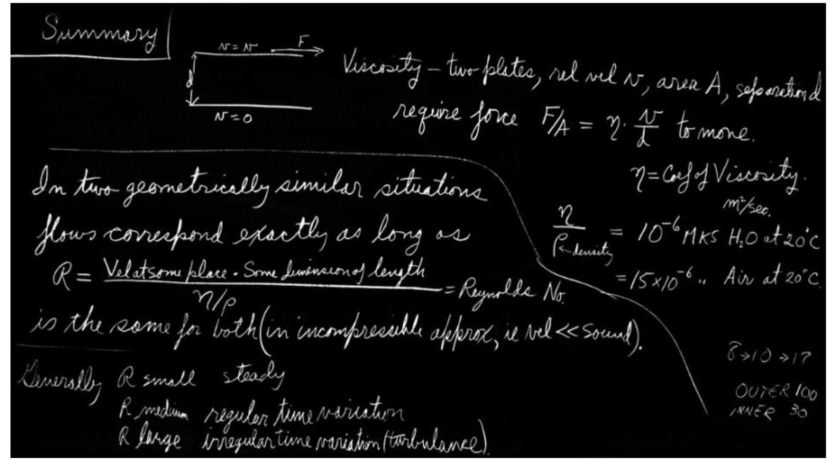
Collaborators: Hong-Yan Shih, Xueying Wang, Tsung-Lin Hsieh, Bjorn Hof, Joachim Mathieson, Gregoire Lemoult, Gaute Linga, Vasudevan Mukund

Supported by NSF & Simons Foundation

Propaganda

Feynman’s vision: RG & Turbulence

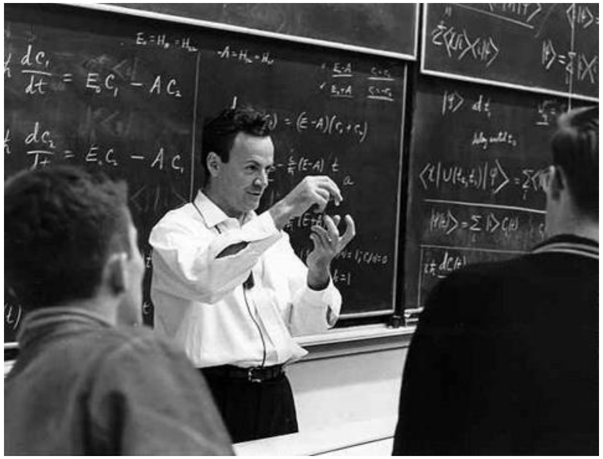


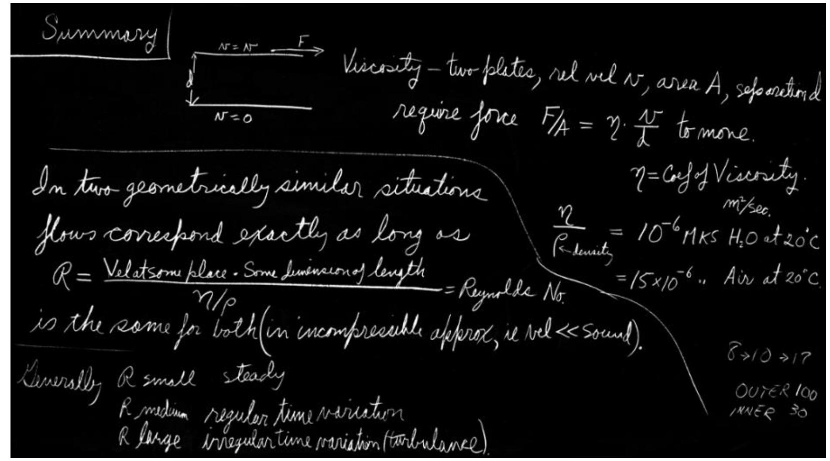


We have written the equations of water flow. From experiment, we find a set of concepts and approximations to use to discuss the solution—vortex streets, turbulent wakes, boundary layers. When we have similar equations in a less familiar situation, and one for which we cannot yet experiment, we try to solve the equations in a primitive, halting, and confused way to try to determine what new ***qualitative*** features may come out, or what new ***qualitative*** forms are a consequence of the equations.

http://www.feynmanlectures.caltech.edu/II_41.html Scientific American

Feynman's vision: RG & Turbulence



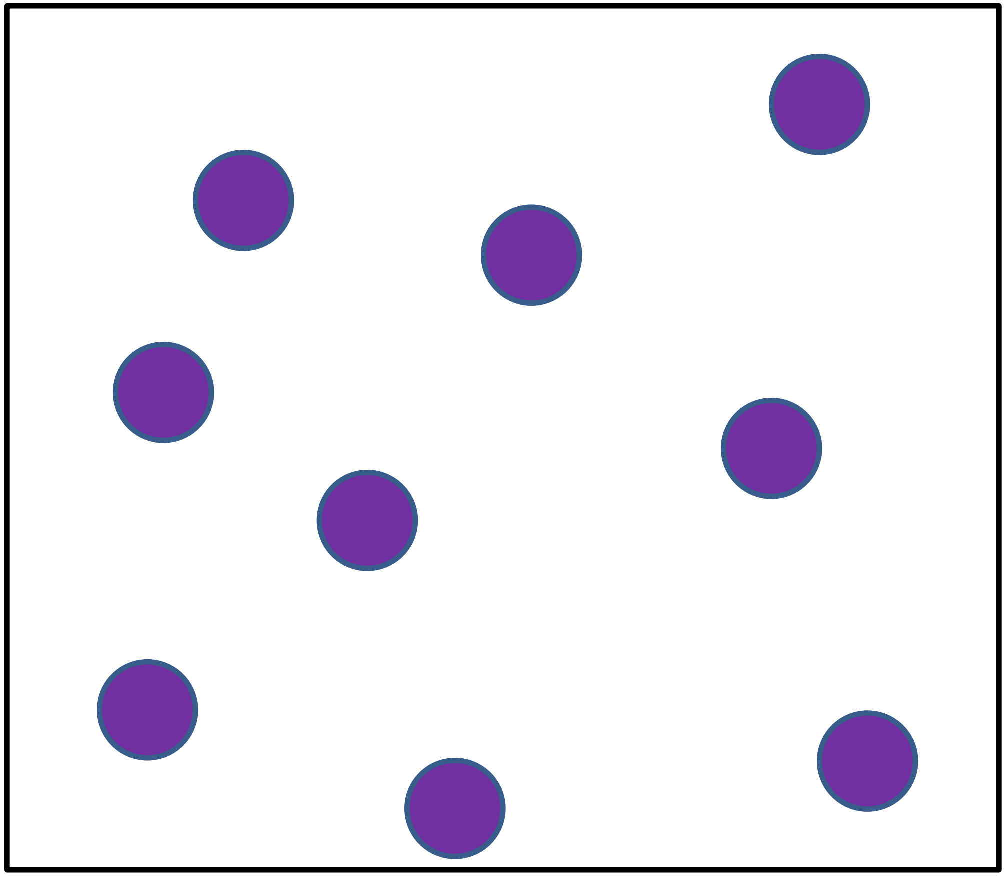


The next great era of awakening of human intellect may well produce a method of understanding the ***qualitative*** content of equations. Today we cannot. Today we cannot see that the water flow equations contain such things as the barber pole structure of turbulence that one sees between rotating cylinders. Today we cannot see whether Schrödinger's equation contains frogs, musical composers, or morality—or whether it does not.

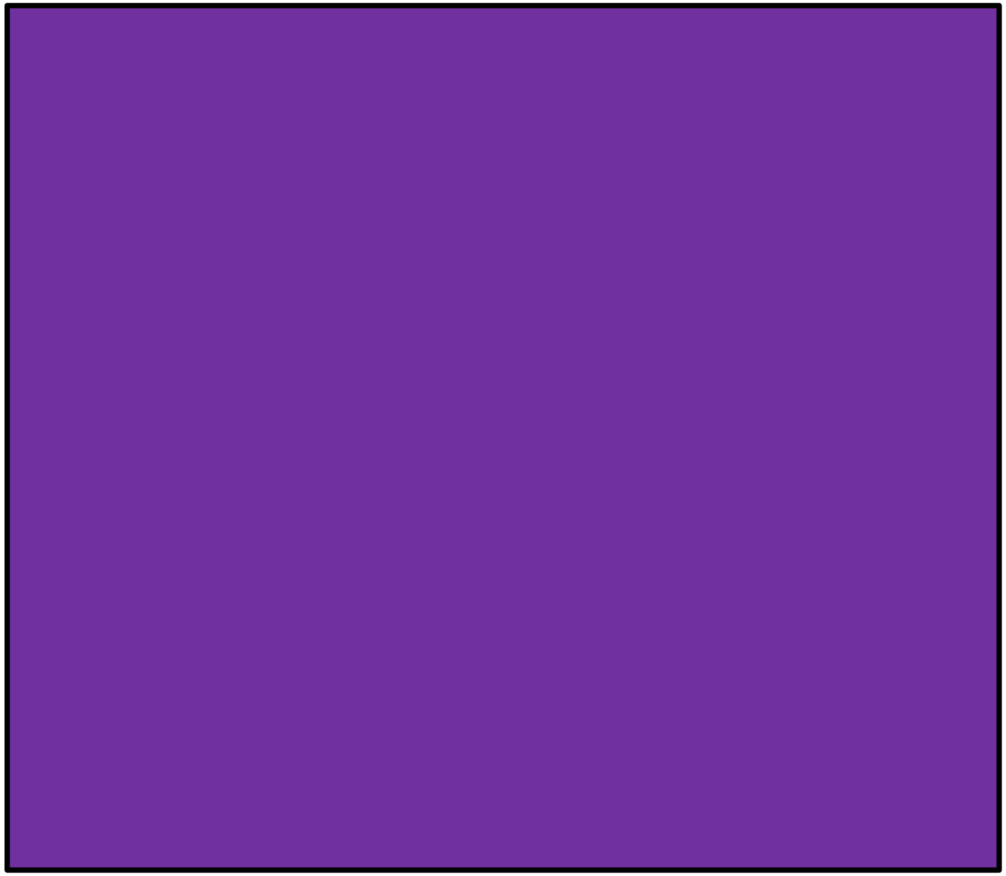
http://www.feynmanlectures.caltech.edu/II_41.html Scientific American

Goal

- The qualitative behavior of matter is the domain of statistical mechanics
- **Our goal: expose the qualitative content of the equations of fluid mechanics, by understanding the phase diagram, universality and scaling laws of turbulence.**
- A start: novel predictions and perspectives based on statistical mechanics.
  - Transitional flows
  - Fluctuation-dissipation relations



Deterministic classical mechanics of many particles in a box ➔ statistical mechanics



Deterministic classical mechanics of infinite number of particles in a box

= Navier-Stokes equations for a fluid

➔ statistical mechanics

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

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

Deterministic classical mechanics of infinite number of particles in a box

= Navier-Stokes equations for a fluid

➔ statistical mechanics

Outline

1. Why are we interested in transitional turbulence?
   i. Turbulent drag and its reduction
   ii. Propagation of turbulent fronts at high Re
   iii. Supercritical transitions to turbulence
   iv. Subcritical transitions to turbulence
2. Puffs
   i. Lifetime of puffs
   ii. Models of puffs
   iii. Directed percolation
   iv. Experimental tests
   v. Puff interactions

Outline

3. Slugs
    i. Phenomenology of slugs
    ii. Streamwise shear in the predator-prey model
    iii. Numerical simulations of extended predator-prey model
    iv. Propagation of turbulent fronts at low Re
4. What we do not understand (yet)
    i. Transitional drag
    ii. Laminar-turbulent transition in 2D
    iii. Connection of statistical mechanics to Navier-Stokes equations and other approaches

1. Transitional turbulence – who cares?

Which part is turbulent?

Which part is turbulent?

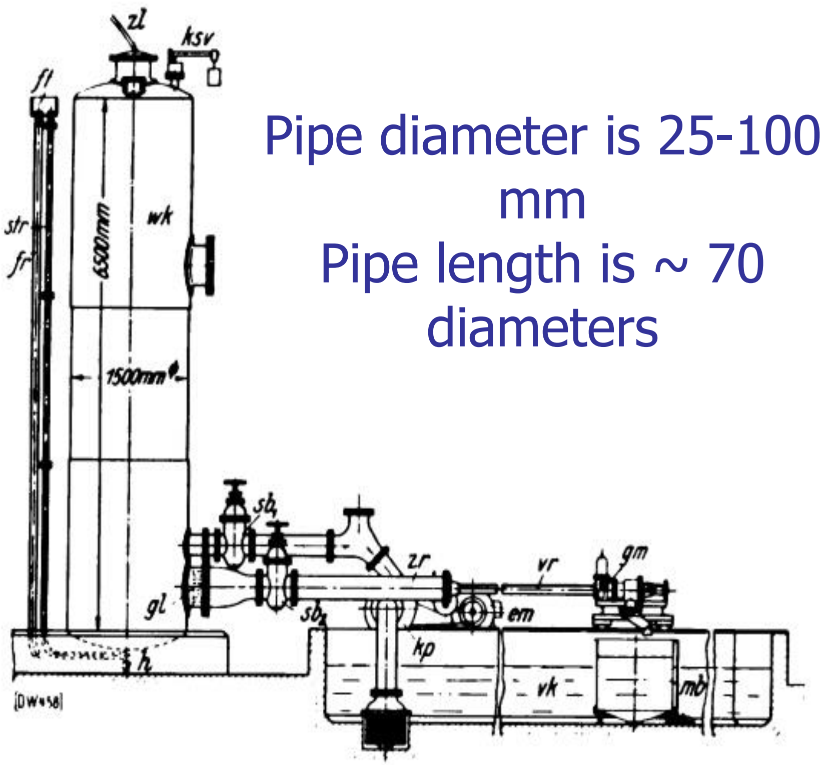
- What we saw:
  - Strong wind speeds
  - Blowing sand
- Did the strong wind cause the sand to fly?

- Did the flying sand cause the strong wind?

- Sand suppresses turbulence
  - Causes turbulence → laminar
  - Speed of laminar >> speed of turbulence

Nikuradse's pipe experiment (1933) to measure the friction factor *f*

$$f = \Delta P / l \rho U^2$$



Pipe diameter is 25-100 mm
Pipe length is ~ 70 diameters

Figure 3.- Test apparatus.

em = electric motor
kp = centrifugal pump
vk = supply canal
wk = water tank
vr = test pipe
zl = supply line
str = vertical pipe
fr = overflow pipe
ft = trap
h = outlet valve
zr = feed line
mb = measuring tank
gm = velocity measuring device
ksv = safety valve on water tank
sb_1 = gate valve between wk and kp
sb_2 = gate valve between wk and zr
gl = baffles for equalizing flow

Monodisperse sand grains 0.8mm glued to sides of pipe

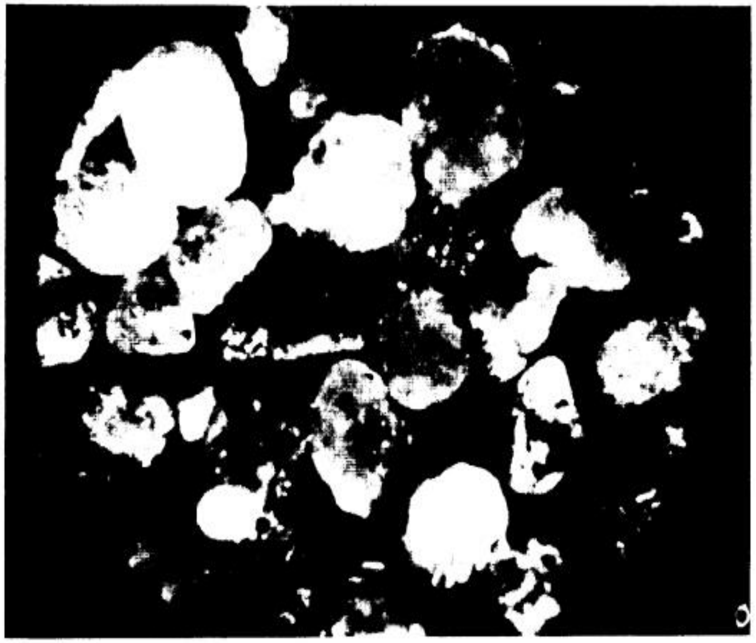
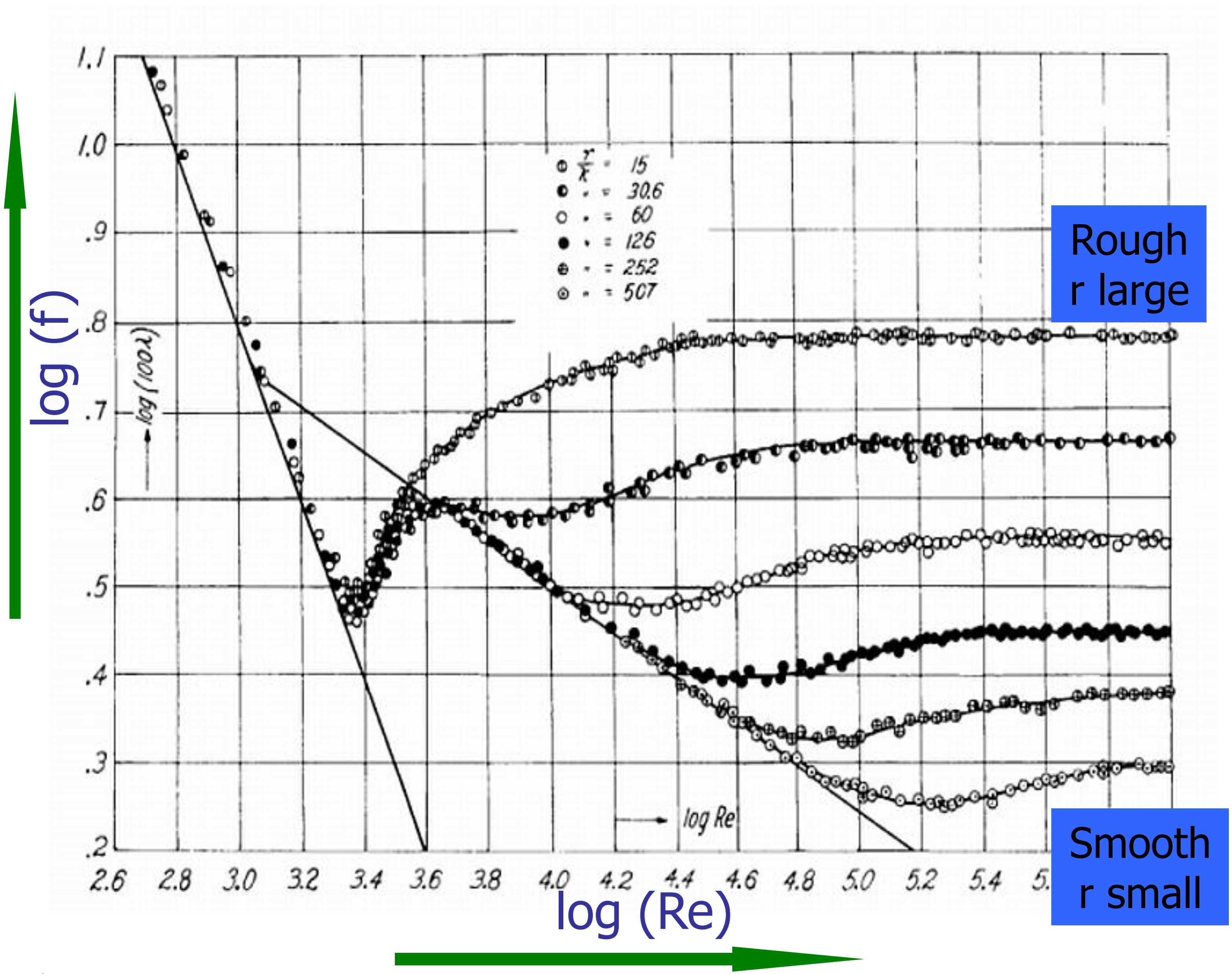


Figure 4.- Microphotograph of sand grains which produce uniform roughness. (Magnified about 20 times.)

Friction factor in turbulent rough pipes



Nikuradse (1933)

Blackboard interlude 1

- Drag in turbulence
- How does the laminar-turbulence interface propagate?
- Why is the laminar-turbulence interface sharp?

End of lecture 1