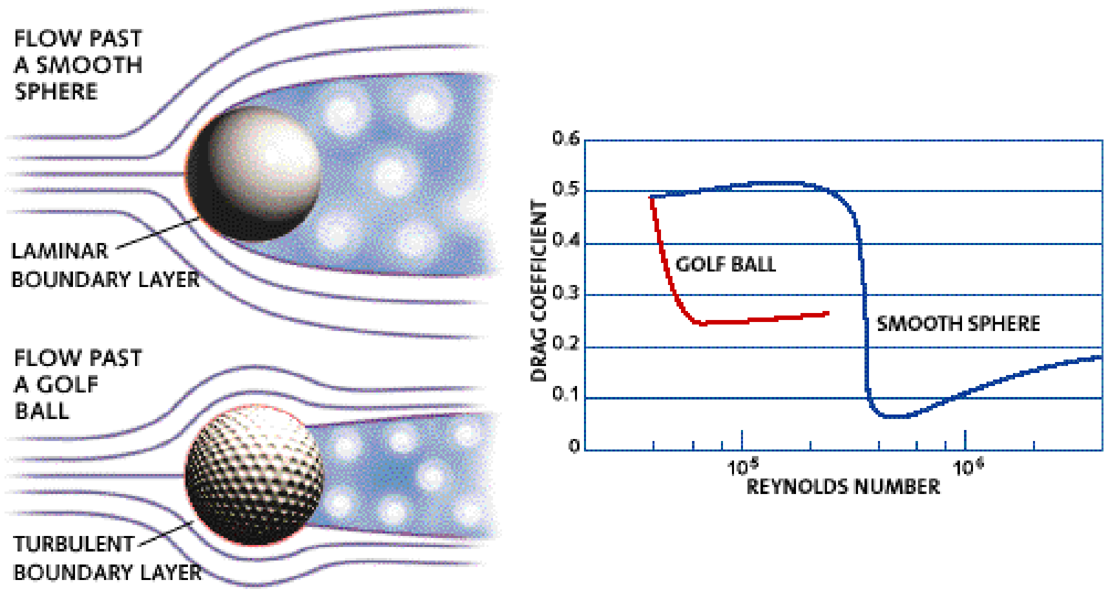
Name: ______________________________
Partner(s): ___________________________
1101 Section: __________
Desk # _______________
Date: ________________

Why do Golf Balls have Dimples on Their Surfaces?



Purpose: To study the drag force on objects with different surfaces, with the help of a wind tunnel.

Overview

In this experiment, we will use a wind tunnel to study how the flow of air, over various balls, gives rise to a drag force.

You saw in the "Falling Cat" lab that the air resistance, or the drag force, increases as the speed increases. We mathematically modelled this drag force as:

$$F_D = bv^2$$

Here, b is a coefficient that takes the shape of the object into account, along with other factors like what the object is falling through. If we further break down b into its parts, we can see this drag force in even more detail.

Separating out the cross sectional area A of the object, and the density of the fluid ρ, the equation becomes

$$F_D = \frac{1}{2} C_D \rho A v^2 \tag{1}$$

where C_D is a dimensionless quantity known as the drag coefficient. It is affected by the object's features, like the shape, the material etc. At low speeds, it is approximately constant, which means the drag force is proportional to v^2.

However, at high speeds, the drag coefficient changes, and the situation becomes rather more complicated. Figure 1 shows the drag coefficient of a ball moving in air.

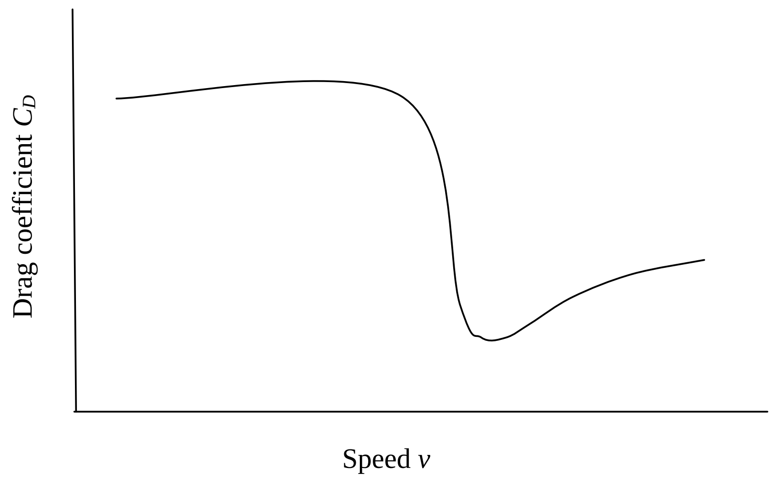


Figure 1

For aerodynamics, it is important to know the drag coefficient at low and high speeds. There are no theoretical equations for it, so it can only be measured experimentally. That is what we are doing today.

The steps we will follow are:

- Measure the drag force F_D;
- Measure the cross section area A;
- Measure the speed of air flow v in the wind tunnel;

Once the above measurements are done and the density of the fluid (air) is known, Equation (1) allows us to calculate the drag coefficient C_D. If we do that for different speeds, we can plot C_D vs. the speed and get a curve similar to Figure 1.

Theory: Bernoulli equation

Bernoulli's equation states that for an incompressible fluid, along any streamline of flow, the quantity $P + \frac{1}{2}\rho v^2 + \rho g h$ is a constant, or

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$

where P is the pressure, ρ is the density of the fluid, v is the flow speed and h is the height relative to an arbitrary zero. Streamlines can be thought of as the paths followed by the fluid particles.

Wind tunnel

A wind tunnel is a device that uses a fan to create a region in which air moves with constant velocity. The design is optimized to create a flow that is as smooth as possible in the central test section.

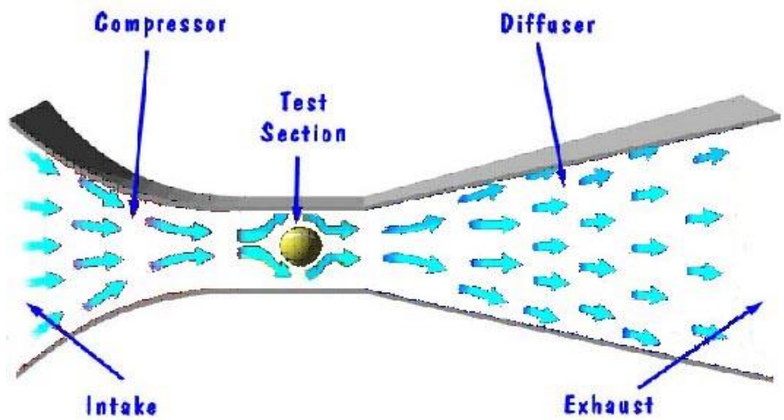
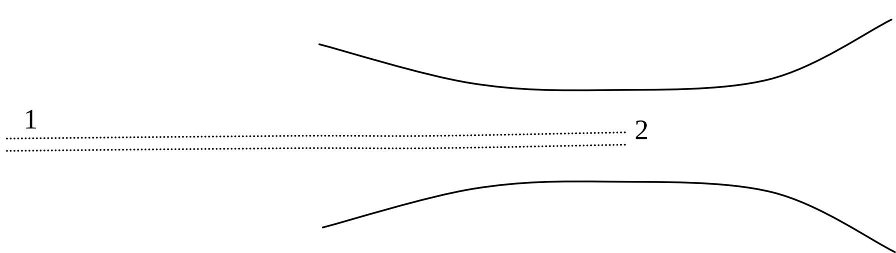


Figure 2: Flow of air through a wind tunnel. A tennis ball is shown mounted in the test section.

Finding the speed of air flow in the wind tunnel

In order to use Bernoulli's equation to eventually find C_D , we will need to go step-by-step. The next couple of pages will take you through the derivations.

Choosing a streamline from far outside the wind tunnel (where the speed of air $v_A = 0$) to the test section,



Bernoulli's equation gives (ρ_A is the density of air):

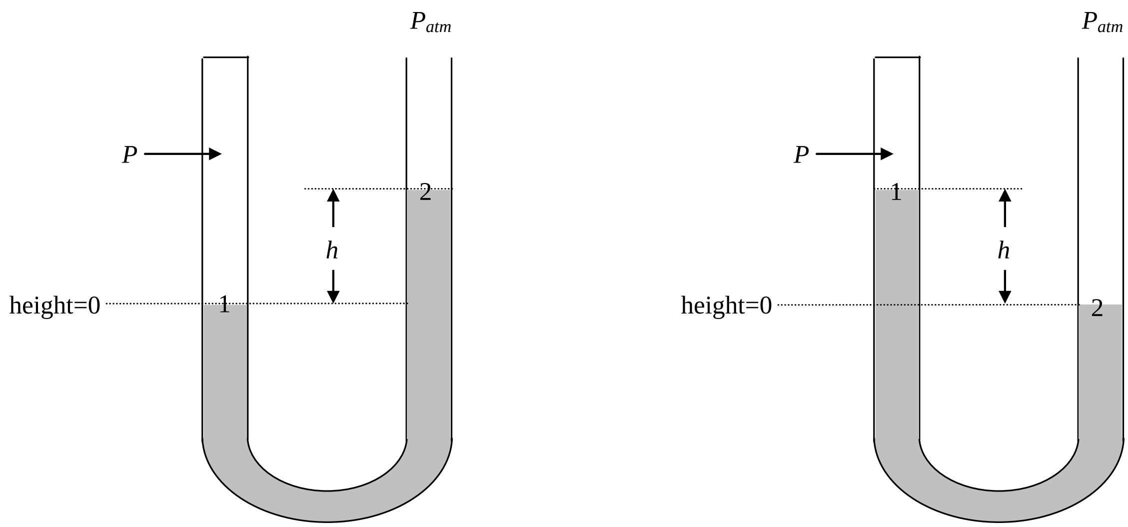
$$P_{atm} + 0 + \rho_A g h = P + \frac{1}{2}\rho_A v^2 + \rho_A g h$$

So v, the speed of air flow in the test section, can be found by measuring the pressure in the test section.

Question 1: In the space below, derive the relation between v and the pressure difference $P_{atm} - P$, assuming the density of air ρ_A is known (symbols only).

Measure the pressure difference with a manometer:

To measure pressure difference, we will use a manometer. A simple manometer is just a U tube with water (density ρ_w) inside:



Bernoulli Equation: $P + 0 + 0 = P_{atm} + 0 + \rho_w gh$
Or: $P - P_{atm} = \rho_w gh$

Bernoulli Equation: $P + 0 + \rho_w gh = P_{atm} + 0 + 0$
Or: $P_{atm} - P = \rho_w gh$

The pressure of the test section in the wind tunnel is lower than atmospheric pressure (the situation on the right). So

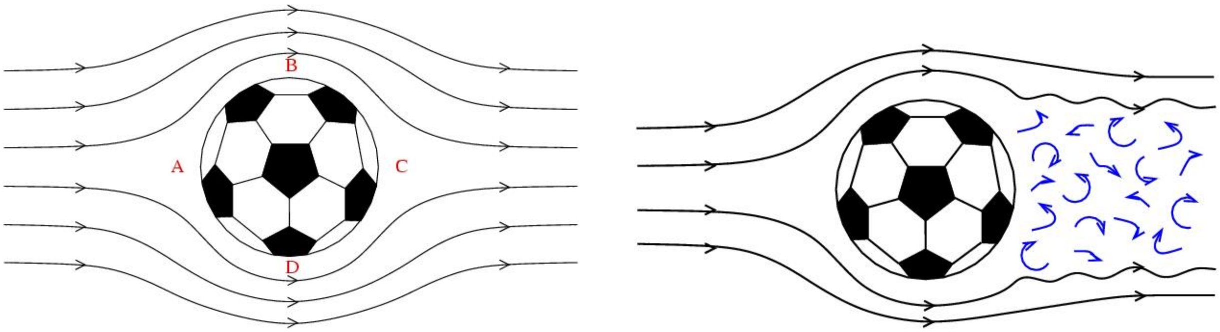
$$P_{atm} - P = \rho_w g h_D$$

where h_D is the reading of the Dwyer manometer attached to the wind tunnel.

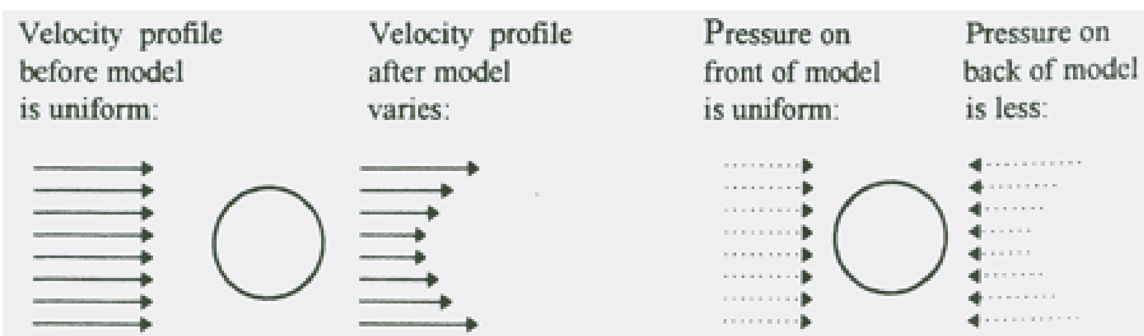
Question 2: In the space below, derive the equation to calculate the speed of air flow v from the reading of the Dwyer manometer (h_D), assuming the density of air ρ_A and the density of water ρ_w are known.

Finding the drag force on a ball

If air had zero viscosity, then the flow of air around a sphere with a smooth surface would be as shown on the left. Notice that the flow is steady and that streamlines both upstream and downstream of the sphere have the same shape. The pressure would thus also the same on both sides, according to Bernoulli's equation. The drag force on the ball would be zero in this - not very realistic - case.



The actual flow around a sphere only resembles this for very low flow speeds. As the speed with which air passes over the surface of the ball increases, the streamlines eventually are unable to follow the contour of the ball, and "separate" from its surface. For a smooth ball, this separation of flow occurs near the widest extent of the ball, as shown on the right hand side of the figure above. Downstream of this the air forms a *wake*. A wake is the region of relatively slowly moving air behind the ball. Comparisons of a velocity profile of air upstream of the ball and in the wake behind it are shown in the figure below.



Because of the pressure difference between the front and back of the ball, there is a net force, which is the drag force, F_D.

In order to find the drag force, 16 little manometers are installed on the downstream side of the ball to measure the pressure difference. The height in each manometer, h_i, measures a pressure difference:

$$\Delta P_i = P_{atm} - P_i = \rho_w g h_i \quad \text{where } i = 1, 2, \ldots, 16$$

Roughly speaking, the average height of the manometer, h_{avg}, will help to measure the average pressure difference ΔP_{avg}. Multiplied by the cross sectional area A, we can get the drag force.

Question 3a: Write the relationship between ΔP_i and h_{avg} .

Question 3b: Calculate the drag force F_D from the average height of 16 manometers h_{avg} and the cross sectional area A. (You are still working in symbols only.)

Finally, we use Equation (1) from page 2, and the answers derived in Questions 2 and 3 to calculate the drag coefficient.

Question 4: Derive the equation to calculate the drag coefficient C_D in the space below.

The derivations are complete. Now we will move on to data and numerical calculations.

Numbers you need in your calculations:

Gravitational acceleration $g = (9.81 \pm 0.01)$ m/s^2

The density of air ρ_A (room temperature) = 1.17 kg/m^3 (±2%)

The density of water $\rho_w = 1.000\times10^3$ kg/m^3 (±0.2%)

The diameter of the golf ball and the rounded golf ball are both: (4.25 ± 0.05) cm

1 inch = 2.54 cm = 0.0254 m

(Uncertainty calculations are not required in this lab. Make all your results to the correct number of significant digits, but remember to not do any rounding during calculations.)

Sample data _____ (assigned A, B or C):

There are 3 sample-data pages available, and one will be given to you in class. In the lab, you will be producing a data set that will look like these, so while you are waiting for your turn at the wind tunnel, you can practice measuring the drag coefficient.

You should have one that is different from your partner, so calculate the following:

1. Calculate the flow speed of wind tunnel.

2. Measure / calculate the average height of 16 manometers in inches.

3. Calculate the cross sectional area *A*.

4. Calculate the average pressure difference across the ball and then the drag force on the ball.

5. Using Equation (1), calculate the drag coefficient C_D.

6. Calculate the drag coefficient using your simplified equation from Question 4.

Wind Tunnel data taking and analysis:

1. Change the speed of the air flow and observe the change of the manometer readings.

2. You will be assigned an airflow speed and a ball to analyze. For your given case, finish a data sheet like the ones in the sample data. Everyone in your group will do their own data sheet.

3. Calculate the drag coefficient C_D *using your simplified equation from Question 4* and enter it in the "1101 Collective Data" sheet. Do the calculation on the back of the data sheet for your case.

4. On the back of the data sheet for your case, do all of the complicated calculations (wind speed, pressure difference, etc.) like you did for the sample data. The drag coefficient should come out the same as the simplified version.

5. Once all of the data for the balls has been collected, the "1101 Collective Data" sheet will be e-mailed to you. Draw the C_D *vs* v curves for both types of ball. You can do this on graph paper or by computer, with both curves on one graph.

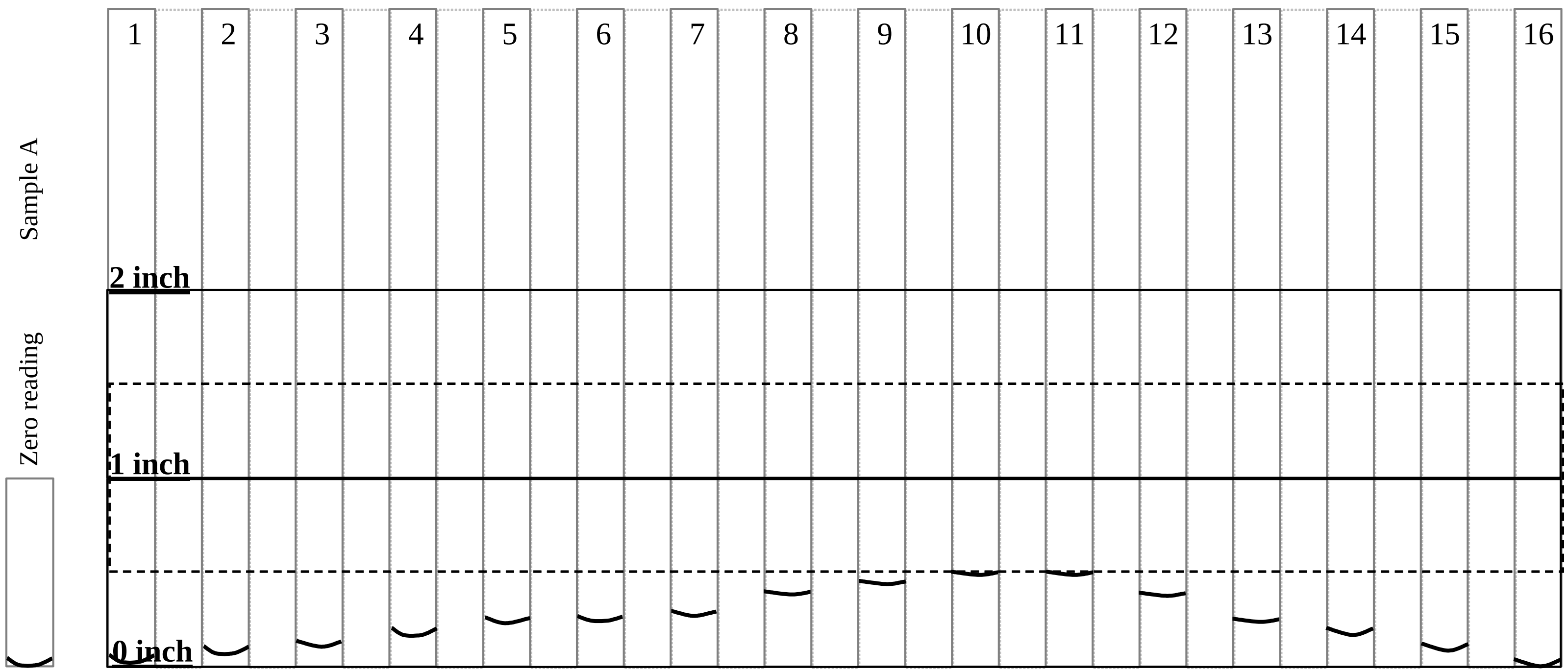
6. Attach your data sheet and the C_D *vs* v curves to this handout.

Review and Discussion

1. Summarize what you can measure with a wind tunnel. What is the purpose of a wind tunnel?

2. Why do golf balls have dimples on their surfaces? Justify your answer by referring to your C_D *vs* v curves from the measurements made in this lab. (Compare the curves for the dimpled and smooth balls.)

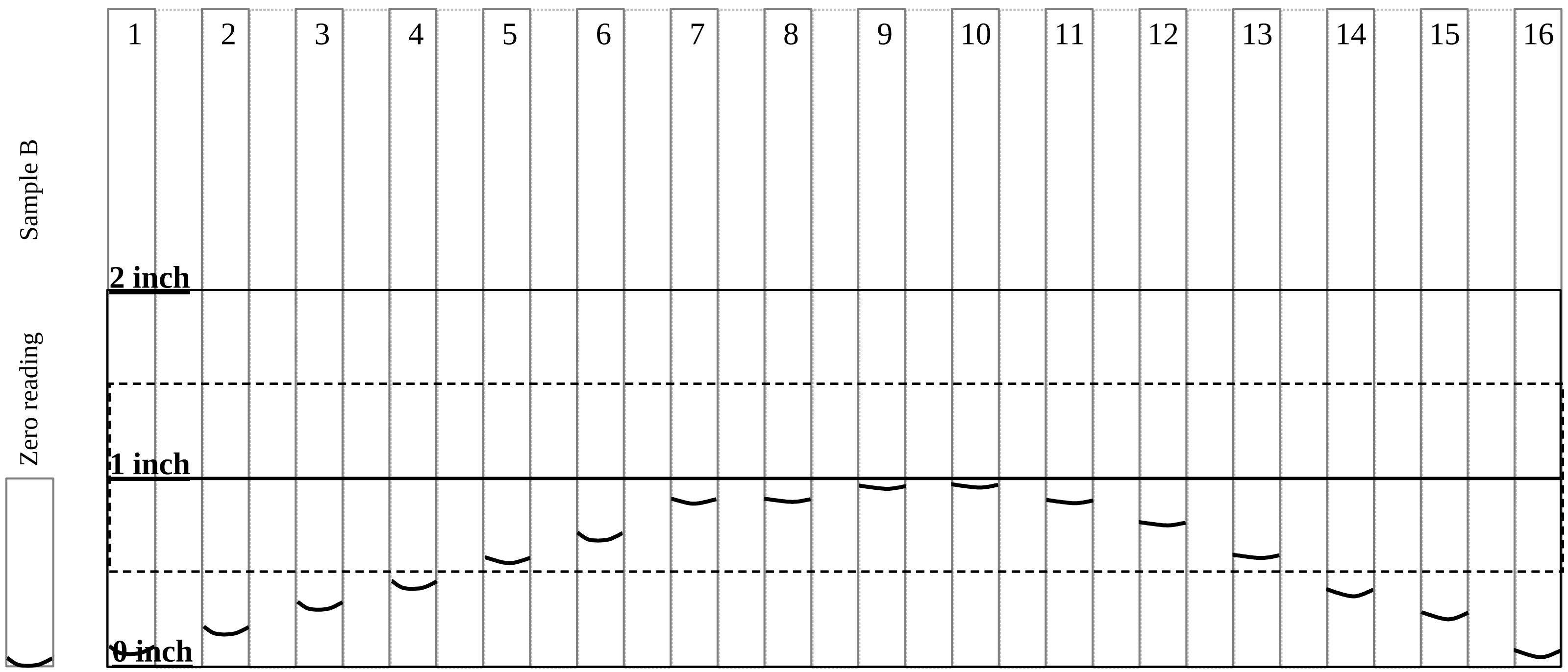
3. What other balls or animals have special surfaces that can strongly affect how they move through fluid? Describe how they work, referring to what you learned in this lab. Note that this is referring to surface texture, not body shape.



Wind Tunnel: red . Ball: dimpled golf ball . Dwyer manometer reading h_D (inch): 1.0 .

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Heights (inch)																

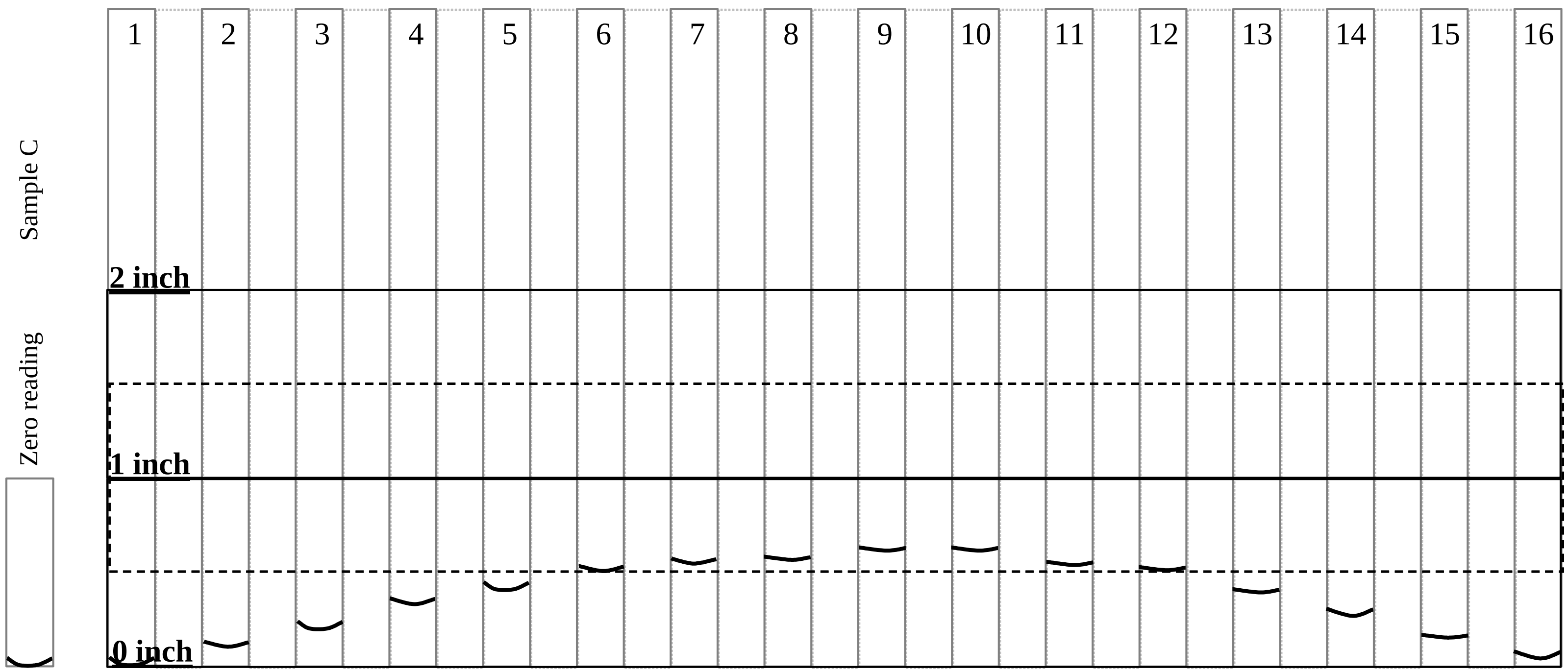
Note: you can measure in inches directly, or measure in millimeters and convert to inches later: 1 inch = 25.4mm



Wind Tunnel: red . Ball: smoothed golf ball . Dwyer manometer reading h_D (inch): 1.0 .

Heights (inch)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Note: you can measure in inches directly, or measure in millimeters and convert to inches later: 1 inch = 25.4mm



Wind Tunnel: red . Ball: dimpled golf ball . Dwyer manometer reading h_D (inch): 1.0 .

Heights (inch)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Note: you can measure in inches directly, or measure in millimeters and convert to inches later: 1 inch = 25.4mm