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(With) Honey, I shrunk the spoon, fork and knife!

Purpose of this exercise: To exercise the concepts of viscosity and Reynolds number while providing an intuition of the behavior of flows and organisms at the low Reynolds numbers where the majority of marine and freshwater organisms operate. This exercise in particular will show students the difficulties that suspension-feeding organisms have in encountering and capturing suspended particles.

Materials required: Although honey will do, corn syrup is cheaper, more transparent and more uniform in viscosity. Two pints will serve for a classroom demonstration that can be passed around. A large beaker or quart jar serves as the container. Also needed are a common household teaspoon, fork and knife, along with a few beads, peas, lentils or beads — ideally of a size just slightly larger than the spacing between the tines of the fork.

Reynolds numbers: The key concept of a Reynolds number is that if the object's shape and orientation to the flow are kept identical, flow patterns will be identical so long as the Reynolds number is kept the same. A Reynolds number, *Re,* is defined as

$$Re = \frac{\rho L U}{\mu}\text{, where} \qquad (1)$$

ρ = the density of the fluid (kg m^{-3}),

L = a length scale for the object (m),

U = the velocity of the fluid before it reaches the object (m s^{-1}), and

μ = the dynamic viscosity of the fluid (kg m^{-1} s^{-1}).

It is common to combine ρ and μ into one parameter, $\nu = \mu/\rho$, making $Re = LU/\nu$. The new parameter is called a kinematic viscosity, with units of m^2 s^{-1}. The combination is convenient in part because all the relevant properties of the fluid are combined into one parameter. It is worth noting that *Re*, then, is not a measure of fluid properties alone, but of the dynamic interaction of a flow with an object. Note that *Re* is nondimensional. That is, the dimensions of its numerator are identical to those of its denominator, allowing them to cancel.

Fluid density is just the mass of fluid contained in a given volume (much larger for lead than for water), and both length and velocity are familiar concepts. Viscosity is less familiar. The units in which it is measured may not be intuitive, but the concept is certainly more so. Viscosity is a measure of the resistance that two sheets of the fluid exert on each other when they are moved in a pattern representing the movement of your two hands rubbing, *i.e.,* a shearing motion. If you want to get an idea of the difference in viscosity among air, water and corn syrup, take a flat piece of material (like a butter knife) and hold sequentially it in (a beaker of) air, a beaker of water and a beaker of corn syrup with its plane parallel to the gravity vector (perpendicular to the floor). Lift up on it. Viscous forces are resisting its motion in proportion to the viscosity of the medium. Only with the syrup do you risk lifting the beaker.

Comments: Scale modeling using Reynolds numbers is more common for making small models of ship and submarine hulls to test performance before scaling to full size than it is for making enlarged models of objects too small to see clearly with the naked eye, but the principles are the same. Humans have a good intuition for high Reynolds numbers because air flowing past a person or a person swimming through the water are both examples of high Reynolds-number flows.

Let's do the calculations for a couple of very familiar cases, a car traveling at 55 mi per hour (× 1.61 km mi^{-1} = 89 km h^{-1} = 8.9 × 10^{4} m h^{-1} = 3.2 × 10^{8} m s^{-1}), and a person standing facing a gentle, 5.0-mi h^{-1} (2.9 × 10^{7} m s^{-1}) breeze (also the speed of a moderately fast walk). Take a moderate-sized car 2.0 m wide and 1.2 m tall. Its maximal cross-sectional area perpendicular to the flow will thus be about 2.4 m^{2}. A logical choice of L for this car is thus $\sqrt{2.4}$ = 1.5 m. From Table 1, I calculate Re = 7.2 × 10^{3}. Take a person 2 m tall and 0.70 m wide, giving a cross-sectional area of this blocky person of 1.4 m^{2} and a characteristic dimension (L) of 1.2 m. I calculate Re = 5.2 × 10^{2}. Neither will show laminar flow patterns downstream. The person is still in the intermediate Re range where coherent eddies are shed, which explains why you get discontinuous whiffs of perfume when someone walks by.

Table 1: Viscosities and densities of some common fluids.

Fluid	μ (kg m^{-1} s^{-1})	ν (m^{2} s^{-1})	ρ(kg m^{-3})
Air (20˚C)	1.82 × 10^{-5}	1.51 × 10^{-5}	1.205
Fresh water (20˚C)	1.01 × 10^{-3}	1.01 × 10^{-6}	998.23
Seawater (salinity 35, 20˚C)	1.09 × 10^{-3}	1.06 × 10^{-6}	1024.76
Corn Syrup (20˚C)*	24	1.7 × 10^{-2}	1360

* Beware, especially in winter, that corn syrup comes in a wide range of viscosities depending upon its sugar composition and water content, and its viscosity is much more temperature sensitive than that of water or air.

Now consider scaling with Re and think about liquids. You may be surprised that, although the dynamic viscosity of air is far lower than that of water, its kinematic viscosity is roughly 15 times higher, so that for the same length and velocity, the Re is actually **lower** in air. Of course it takes more energy to get an equal volume of water up to the same speed as wind, so don't push this point too far (or rather too fast).

As a ballpark estimate, take 2.5 cm as the characteristic dimension of an eating utensil. You are familiar with how they operate in both air and water, which is the reason for choosing them rather than some less familiar but geometrically simpler objects. Let's consider the relation between the flows that they produce in water versus those that they produce in corn syrup. If you move them at the same speed as you normally do (and they obviously keep the same L), the Re will shrink by a factor of 17,000. Conversely, when you work with the utensil in corn syrup, you know that similar flow patterns would result in water if you moved an object at the same speed but shrunk it by the same factor. Thus you are getting an intuition for how things work in water that are 0.025 m/(1.7 × 10^{4}) = 1.5 µm wide!

Check it out. First try to catch a particle with a spoon (no fair using the beaker walls or the air-liquid interface, as these options are not available to the typical planktonic suspension feeder). Notice how much farther away motion of your spoon causes a disturbance than it does in water. Then try the fork. Explain to yourself why it behaves so much differently than you observe in water. You will find that using the knife edge-on will make it easiest to contact a particle. We've perhaps shrunk the utensils a little too much to make them good analogs of metazoan suspension feeders, but they are not bad replicas of appendages on some suspension-feeding protists, and they give a good intuition of the real, fluid mechanical impediments to encounter at low Re.