6.055J / 2.038J The Art of Approximation in Science and Engineering
Spring 2008

8.3 Drag

Pendulum motion is not a horrible enough problem to show the full benefit of dimensional analysis. Instead try fluid mechanics – a subject notorious for its mathematical and physical complexity; Chandrasekhar's books [10, 11] or the classic textbook of Lamb [12] show that the mathematics is not for the faint of heart.

The next examples illustrate two extremes of fluid flow: oozing and turbulent. An example of oozing flow is ions transporting charge in seawater (**Section 8.3.6**). An example of turbulent flow is a raindrop falling from the sky after condensing out of a cloud (**Section 8.3.7**).

To find the terminal velocity, solve the partial-differential equations of fluid mechanics for the incompressible flow of a Newtonian fluid:

Density ρ_{fl}
Viscosity ν

R

ρ_{obj}

v

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{v}, \qquad \text{(3 eqns)}$$

$$\nabla\cdot\mathbf{v} = 0. \qquad \text{(1 eqn)}$$

Here $\mathbf{v}$ is the fluid velocity, ρ is the fluid density, ν is the kinematic viscosity, and p is the pressure. The first equation is a vector shorthand for three equations, so the full system is four equations.

All the equations are partial-differential equations and three are nonlinear. Worse, they are coupled: Quantities appear in more than one equation. So we have to solve a system of coupled, nonlinear, partial-differential equations. This solution must satisfy boundary conditions imposed by the marble or raindrop. As the object moves, the boundary conditions change. So until you know how the object moves, you do not know the boundary conditions. Until you know the boundary conditions, you cannot find the motion of the fluid or of the object. This coupling between the boundary conditions and solution compounds the difficulty of the problem. It requires that you solve the equations and the boundary conditions together. If you ever get there, then you take the limit $t \to \infty$ to find the terminal velocity.

Sleep easy! I wrote out the Navier–Stokes equations only to scare you into using dimensional analysis and special-cases reasoning. The approximate approach is easier than solving nonlinear partial-differential equations.

8.3.1 Naive dimensional analysis

To use dimensional analysis, follow the usual steps: Choose relevant variables, form dimensionless groups from them, and solve for the terminal velocity. In choosing quantities, do not forget to include the variable for which you are solving, which here is v. To decide on the other quantities, split them into three categories (divide and conquer):

1. characteristics of the fluid,

2. characteristics of the object, and

3. characteristics of whatever makes the object fall.
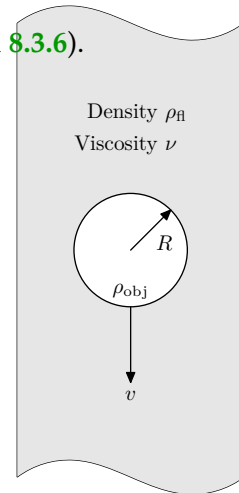
The last category is the easiest to think about, so deal with it first. Gravity makes the object fall, so g is on the list.

Consider next the characteristics of the object. Its velocity, as the quantity for which we are solving, is already on the list. Its mass m affects the terminal velocity: A feather falls more slowly than a rock does. Its radius r probably affects the terminal velocity. Instead of listing r and m together, remix them and use r and ρ_{obj}. The two alternatives r and m or r and ρ_{obj} provide the same information as long as the object is uniform: You can compute ρ_{obj} from m and r and can compute m from ρ_{obj} and r.

Choose the preferable pair by looking ahead in the derivation. The relevant properties of the fluid include its density ρ_{fl}. If the list also includes ρ_{obj}, then the results might contain pleasing dimensionless ratios such as ρ_{obj}/ρ_{fl} (a dimensionless group!). The ratio ρ_{obj}/ρ_{fl} has a more obvious physical interpretation than a combination such as $m/\rho_{fl}r^3$, which, except for a dimensionless constant, is more obscurely the ratio of object and fluid densities. So choose ρ_{obj} and r over m and r.

Scaling arguments also favor the pair ρ_{obj} and r. In a scaling argument you imagine varying, say, a size. Size, like heat, is an extensive quantity: a quantity related to amount of stuff. When you vary the size, you want as few other variables as possible to change so that those changes do not obscure the effect of changing size. Therefore, whenever possible replace extensive quantities with **intensive quantities** like temperature or density. The pair m and r contains two extensive quantities, whereas the preferable pair ρ_{obj} and r contains only one extensive quantity.

Now consider properties of the fluid. Its density ρ_{fl} affects the terminal velocity. Perhaps its viscosity is also relevant. Viscosity measures the tendency of a fluid to reduce velocity differences in the flow. You can observe an analog of viscosity in traffic flow on a multilane highway. If one lane moves much faster than another, drivers switch from the slower to the faster lane, eventually slowing down the faster lane. Local decisions of the drivers reduce the velocity gradient. Similarly, molecular motion (in a gas) or collisions (in a fluid) transports speed (really, momentum) from fast- to slow-flowing regions. This transport reduces the velocity difference between the regions. Oozier (more viscous) fluids probably produce more drag than thin fluids do. So viscosity belongs on the list of relevant variables.

Fluid mechanicians have defined two viscosities: dynamic viscosity η and kinematic viscosity ν. [Sadly, we could not use the mellifluous term *fluid mechanics* to signify a host of physicists agonizing over the equations of fluid mechanics; it would not distinguish the toilers from their toil.] The two viscosities are related by $\eta = \rho_{fl}\nu$. *Life in Moving Fluids* [13, pp. 23–25] discusses the two types of viscosity in detail. For the analysis of drag force, you need to know only that viscous forces are proportional to viscosity. Which viscosity should we use? Dynamic viscosity hides ρ_{fl} inside the product $\nu\rho_{fl}$; a ratio of ρ_{obj} and η then looks less dimensionless than it is because ρ_{obj}'s partner ρ_{fl} is buried inside η. Therefore the kinematic viscosity ν usually gives the more insightful results. Summarizing the discussion, the table lists the variables by category.

The next step is to find dimensionless groups. The Buck-
ingham Pi theorem (**Section 7.6**) says that the six vari-
ables and three independent dimensions result in three
dimensionless groups.

Var	Dim	What
ν	L^2T^{-1}	kinematic viscosity
ρ_{fl}	ML^{-3}	fluid density
r	L	object radius
v	LT^{-1}	terminal velocity
ρ_{obj}	ML^{-3}	object density
g	LT^{-2}	gravity

Before finding the groups, consider the consequences of
three groups. Three?! Three dimensionless groups pro-
duce this form for the terminal velocity v:

$$\text{group with } v = f(\text{other group 1}, \text{other group 2}).$$

To deduce the properties of f requires physics knowledge. However, studying a two-
variable function is onerous. A function of one variable is represented by a curve and
can be graphed on a sheet of paper. A function of two variables is represented by a sur-
face. For a complete picture it needs three-dimensional paper (do you have any?); or you
can graph many slices of it on regular two-dimensional paper. Neither choice is appeal-
ing. This brute-force approach to the terminal velocity produces too many dimensionless
groups.

If you simplify only after you reach the complicated form

$$\text{group with } v = f(\text{other group 1}, \text{other group 2}),$$

you carry baggage that you eventually discard. When going on holiday to the Caribbean,
why pack skis that you never use but just cart around everywhere? Instead, at the be-
ginning of the analysis, incorporate the physics knowledge. That way you simplify the
remainder of the derivation. To follow this strategy of packing light – of packing only what
you need – consider the physics of terminal velocity in order to make simplifications now.

8.3.2 Simpler approach

The adjective *terminal* in the phrase 'terminal velocity' hints at the physics
that determines the velocity. Here 'terminal' is used in its sense of final,
as in after an infinite time. It indicates that the velocity has become con-
stant, which happens only when no net force acts on the marble. This
line of thought suggests that we imagine the forces acting on the object: gravity, buoyancy,
and drag. The terminal velocity is velocity at which the drag, gravitational, and buoyant
forces combine to make zero net force. Divide-and-conquer reasoning splits the terminal-
velocity problem into three simpler problems.
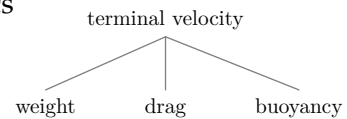
The gravitational force, also known as the weight, is mg. Instead of m
we use $(4\pi/3)\rho_{obj}r^3$ – for the same reasons that we listed ρ_{obj} instead of
m in the table of variables – and happily ignore the factor of $4\pi/3$. With
those choices, the weight is

$$F_g \sim \rho_{obj}r^3g.$$
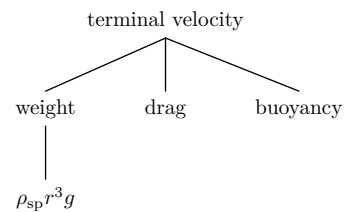
The figure shows the roadmap updated with this information.

The remaining pieces are drag and buoyancy. Buoyancy is easier, so do it first (the principle of maximal laziness). It is an upward force that results because gravity affects the pressure in a fluid. The pressure increases according to $p = p_0 + \rho_{fl}gh$, where h is the depth and p_0 is the pressure at zero depth (which can be taken to be at any level in the fluid). The pressure difference between the top and bottom of the object, which are separated by a distance $\sim r$, is $\Delta p \sim \rho_{fl}gr$. Pressure is force per area, and the pressure difference acts over an area $A \sim r^2$. Therefore the buoyant force created by the pressure difference is

$$F_b \sim A\Delta p \sim \rho_{fl}r^3 g.$$

As a check on this result, Archimedes's principle says that the buoyant force is the 'weight of fluid displaced'. This weight is

$$\rho_{fl} \overbrace{\frac{4\pi}{3}\pi r^3}^{mass}\underbrace{\phantom{\frac{4\pi}{3}\pi r^3}}_{volume} g.$$

Except for the factor of $4\pi/3$, it matches the buoyant force so Archimedes's principle confirms our estimate for F_b. That result updates the roadmap. The main unexplored branch is the drag force, which we solve using dimensional analysis.
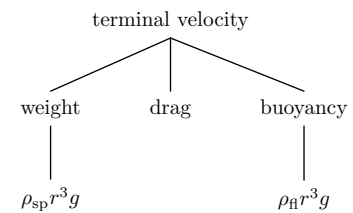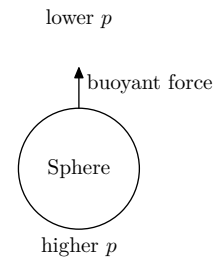
8.3.3 Dimensional analysis for the drag force

The weight and buoyancy were solvable without dimensional analysis, but we still need to use dimensional analysis to find the drag force. The purpose of breaking the problem into parts was to simplify this dimensional analysis relative to the brute-force approach in **Section 8.3.1**. Let's see how the list of variables changes when computing the drag force rather than the terminal velocity. The drag force F_d has to join the list: not a promising beginning when trying to eliminate variables. Worse, the terminal velocity v remains on the list, even though we are no longer computing it, because the drag force depends on the velocity of the object.

However, all is not lost. The drag force has no idea what is inside the sphere. Picture the fluid as a huge computer that implements the laws of fluid dynamics. From the viewpoint of this computer, the parameters v and r are the only relevant attributes of a moving sphere. What lies underneath the surface does not affect the fluid flow: Drag is only skin deep. The computer can determine the flow (if it has tremendous processing power) without knowing the sphere's density ρ_{obj}, which means it vanishes from the list. Progress!

Now consider the characteristics of the fluid. The fluid supercomputer still needs the density and viscosity of the fluid to determine how the pieces of fluid move in response to the object's motion. So ρ_{fl} and ν remain on the list. What about gravity? It causes the object to fall, so it is responsible for the terminal velocity v. However, the fluid supercomputer does not care how the object acquired this velocity; it cares only what the velocity is.

| Var	Dim	What
F_d	MLT^{-2}	drag force
ν	L^2T^{-1}	kinematic viscosity
ρ_{fl}	ML^{-3}	fluid density
r	L	object radius
v	LT^{-1}	terminal velocity

So g vanishes from the list. The updated tabled shows the new, shorter list.

The five variables in the list are composed of three basic dimensions. From the Buckingham Pi theorem (**Section 7.6**), we expect two dimensionless groups. We find one group by dividing and conquering. The list already includes a velocity (the terminal velocity). If we can concoct another quantity V with dimensions of velocity, then v/V is a dimensionless group. The viscosity ν is almost a velocity. It contains one more power of length than velocity does. Dividing by r eliminates the extra length: $V \equiv \nu/r$. A dimensionless group is then

$$G_1 \equiv \frac{v}{V} = \frac{vr}{\nu}.$$
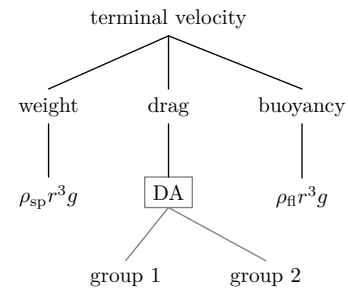
Our knowledge, including this group, is shown in the figure. This group is so important that it has a name, the **Reynolds number**, which is abbreviated *Re*. It is important because it is a *dimensionless* measure of flow speed. The velocity, because it contains dimensions, cannot distinguish fast from slow flows. For example, $1000 \, \mathrm{m \, s^{-1}}$ is slow for a planet, whose speeds are typically tens of kilometers per second, but fast for a pedestrian. When you hear that a quantity is small, fast, large, expensive, or almost any adjective, your first reaction should be to ask, 'compared to what?' Such a comparison suggests dividing v by another velocity; then we get a dimensionless quantity that is proportional to v. The result of this division is the Reynolds number.
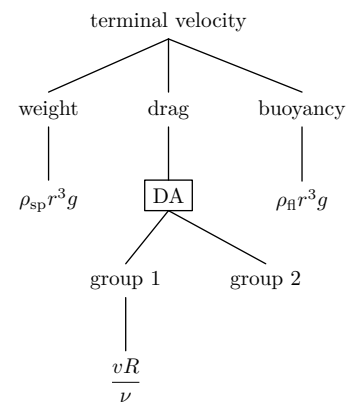
Low values of *Re* indicate slow, viscous flow (cold honey oozing out of a jar). High values indicate turbulent flow (a jet flying at 600 mph). The excellent *Life in Moving Fluids* [13] discusses many more dimensionless ratios that arise in fluid mechanics.

The Reynolds number looks lonely in the map. To give it company, find a second dimensionless group. The drag force is absent from the first group so it must live in the second; otherwise we cannot solve for the drag force.

Instead of dreaming up the dimensionless group in one lucky guess, we construct it in steps (divide-and-conquer reasoning). Examine the variables in the table, dimension by dimension. Only two (F_d and ρ_{fl}) contain mass, so both or neither appear in the group. Because F_d has to appear, ρ_{fl} must also appear. Each variable contains a first power of mass, so the group contains the ratio F_d/ρ_{fl}. A simple choice is

$$G_2 \propto \frac{F_{\mathrm{d}}}{\rho_{\mathrm{fl}}}.$$

The dimensions of $F_{\mathrm{d}}/\rho_{\mathrm{fl}}$ are L^4T^{-2}, which is the square of L^2T^{-1}. Fortune smiles on us, for L^2T^{-1} are the dimensions of v. So
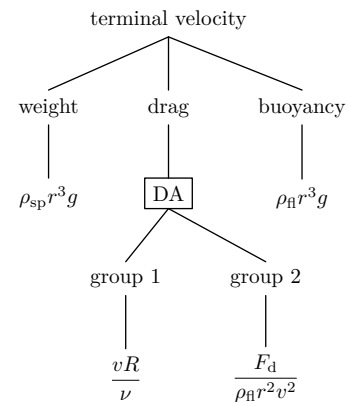
$$\frac{F_{\mathrm{d}}}{\rho_{\mathrm{fl}}v^2}$$

is a dimensionless group.

This choice, although valid, has a defect: It contains v, which already belongs to the first group (the Reynolds number). Of all the variables in the problem, v is the one most likely to be found irrelevant based on a physical argument (as will happen in **Section 8.3.7**, when we specialize to high-speed flow. If v appears in two groups, eliminating it requires recombining the two groups into one that does not contain v. However, if v appears in only one group, then eliminating it is simple: eliminate that group. Simpler mathematics – eliminating a group rather than remixing two groups to get one group – requires simpler physical reasoning. Therefore, isolate v in one group if possible.

To remove v from the proposed group $F_{\mathrm{d}}/\rho_{\mathrm{fl}}v^2$ notice that the product of two dimensionless groups is also dimensionless. The first group contains v^{-1} and the proposed group contains v^{-2}, so the ratio

$$\frac{\text{group proposed}}{(\text{first group})^2} = \frac{F_{\mathrm{d}}}{\rho_{\mathrm{fl}}r^2v^2}$$

is not only dimensionless but it also does not contain v. So the analysis will be easy to modify when we try to eliminate v. With this revised second group, our knowledge is now shown in this figure:

This group, unlike the the proposal $F_{\mathrm{d}}/\rho_{\mathrm{fl}}v^2$, has a plausible physical interpretation. Imagine that the sphere travels a distance l, and use l to multiply the group by unity:

$$\underbrace{\frac{F_{\mathrm{d}}}{\rho_{\mathrm{fl}}r^2v^2}}_{\textit{group 1}} \times \underbrace{\frac{l}{l}}_{1} = \frac{F_{\mathrm{d}}l}{\rho_{\mathrm{fl}}lr^2v^2}.$$

The numerator is the work done against the drag force over the distance l. The denominator is also an energy. To interpret it, examine its parts (divide and conquer). The product lr^2 is, except for a dimensionless constant, the volume of fluid swept out by the object. So $\rho_{\mathrm{fl}}lr^2$ is, except for a constant, the mass of fluid shoved aside by the object. The object moves fluid with a velocity comparable to v, so it imparts to the fluid a kinetic energy

$$E_{\mathrm{K}} \sim \rho_{\mathrm{fl}}lr^2v^2.$$

Thus the ratio, and hence the group, has the following interpretation:

$$\frac{\text{work done against drag}}{\text{kinetic energy imparted to the fluid}}.$$

In highly dissipative flows, when energy is burned directly up by viscosity, the numerator is much larger than the denominator, so this ratio (which will turn out to measure drag) is much greater than 1. In highly streamlined flows (a jet wing), the the work done against drag is small because the fluid returns most of the imparted kinetic energy to the object. So in the ratio, the numerator will be small compared to the denominator.

To solve for F_d, which is contained in G_2, use the form $G_2 = f(G_1)$, which becomes

$$\frac{F_d}{\rho_{fl} r^2 v^2} = f\left(\frac{vr}{\nu}\right).$$

The drag force is then

$$F_d = \rho_{fl} r^2 v^2 \, f\left(\frac{vr}{\nu}\right).$$

The function f is a dimensionless function: Its argument is dimensionless and it returns a dimensionless number. It is also a universal function. The same f applies to spheres of any size, in a fluid of any viscosity or density! Although f depends on r, ρ_{fl}, ν, and v, it depends on them only through one combination, the Reynolds number. A function of one variable is easier to study than is a function of four variables:

> A good table of functions of one variable may require a page; that of a function of two variables a volume; that of a function of three variables a bookcase; and that of a function of four variables a library.
>
> —Harold Jeffreys [6, p. 82]

Dimensional analysis cannot tell us the form of f. To learn its form, we specialize to two special cases:

1. viscous, low-speed flow ($Re \ll 1$), the subject of **Section 8.3.4**; and

2. turbulent, high-speed flow ($Re \gg 1$), the subject of **Section 8.3.7**.

8.3.4 Viscous limit

As an example of the low-speed limit, consider a marble falling in vegetable oil or glycerin. You may wonder how often marbles fall in oil, and why we bother with this example. The short answer to the first question is 'not often'. However, the same physics that determines the fall of marbles in oil also determines, for example, the behavior of fog droplets in air, of bacteria swimming in water [14], or of oil drops in the Millikan oil-drop experiment. The marble problem not only illustrates the physical principles, but also we can check our results with a home experiment.

In slow, viscous flows, the drag force comes directly from – surprise! – viscous forces. These forces are proportional to viscosity because viscosity is the constant of proportionality in the definition of the viscous force. Therefore

$$F_d \propto \nu.$$

The viscosity appears exactly once in the drag result, repeated here:

$$F_d = \rho_{fl} r^2 v^2 f\left(\frac{vr}{\nu}\right).$$

To flip ν into the numerator and make $F_d \propto \nu$, the function f must have the form $f(x) \sim 1/x$. With this $f(x)$ the result is

$$F_d \sim \rho_{fl} r^2 v^2 \frac{\nu}{vr} = \rho_{fl}\nu v.$$

Dimensional analysis alone is insufficient to compute the missing magic dimensionless constant. A fluid mechanician must do a messy and difficult calculation. Her burden is light now that we have worked out the solution except for this one constant. The British mathematician Stokes, the first to derive its value, found that

$$F_d = 6\pi\rho_{fl}\nu vr.$$

In honor of Stokes, this result is called Stokes drag.

Let's sanity check the result. Large or fast marbles should feel a lot of drag, so r and v should be in the numerator. Viscous fluids should produce a lot of drag, so ν should be the numerator. The proposed drag force passes these tests. The correct location of the density – in the numerator or denominator – is hard to judge.

You can make an educated judgment by studying the Navier–Stokes equations. In those equations, when v is 'small' (small compared to what?) then the $(\mathbf{v}\cdot\nabla)\mathbf{v}$ term, which contains two powers of v, becomes tiny compared to the viscous term $\nu\nabla^2\mathbf{v}$, which contains only one power of v. The second-order term arises from the inertia of the fluid, so this term's being small says that the oozing marble does not experience inertial effects. So perhaps ρ_{fl}, which represents the inertia of the fluid, should not appear in the Stokes drag. On the other hand, viscous forces are proportional to the *dynamic* viscosity $\eta = \rho_{fl}\nu$, so ρ_{fl} should appear even if inertia is unimportant. The Stokes drag passes this test. Using the dynamic instead of kinematic viscosity, the Stokes drag is

$$F_d = 6\pi\eta vr,$$

often a convenient form because many tables list η rather than ν.

This factor of 6π comes from doing honest calculations. Here, it comes from solving the Navier–Stokes equations. In this book we wish to teach you how not to suffer, so we do not solve such equations. We usually quote the factor from honest calculation to show you how accurate (or sloppy) the approximations are. The factor is often near unity, although not in this case where it is roughly 20! In fancy talk, it is usually 'of order unity'. Such a number suits our neural hardware: It is easy to remember and to use. Knowing the approximate derivation and remembering this one number, you reconstruct the exact result without solving difficult equations.

Now use the Stokes drag to estimate the terminal velocity in the special case of low Reynolds number.

8.3.5 Terminal velocity for low Reynolds number

Having assembled all the pieces in the roadmap, we now return to the original problem of finding the terminal velocity. Since no net force acts on the marble (the definition of terminal velocity), the drag force plus the buoyant force equals the weight:

$$\underbrace{\nu\rho_{fl}\nu r}_{F_d} + \underbrace{\rho_{fl}gr^3}_{F_b} \sim \underbrace{\rho_{obj}gr^3}_{F_g}.$$

After rearranging:

$$\nu\rho_{fl}\nu r \sim (\rho_{obj} - \rho_{fl})gr^3.$$

The terminal velocity is then

$$v \sim \frac{gr^2}{\nu}\left(\frac{\rho_{obj}}{\rho_{fl}} - 1\right).$$

In terms of the dynamic viscosity η, it is

$$v \sim \frac{gr^2}{\eta}(\rho_{obj} - \rho_{fl}).$$

This version, instead of having the dimensionless factor $\rho_{obj}/\rho_{fl} - 1$ that appears in the version with kinematic viscosity, has a dimensional $\rho_{obj} - \rho_{fl}$ factor. Although it is less aesthetic, it is often more convenient because tables often list dynamic viscosity η rather than kinematic viscosity ν.

We can increase our confidence in this expression by checking whether the correct variables are upstairs (a picturesque way to say 'in the numerator') and downstairs (in the denominator). Denser marbles should fall faster than less dense marbles, so ρ_{obj} should live upstairs. Gravity accelerates marbles, so g should live upstairs. Viscosity slows marbles, so ν should live downstairs. The terminal velocity passes these tests. We therefore have more confidence in our result, although the tests did not check the location of r or any exponents: For example, should ν appear as ν^2? Who knows, but if viscosity matters, it mostly appears as a square root or as a first power.

To check r, imagine a large marble. It will experience a lot of drag and fall slowly, so r should appear downstairs. However, large marbles are also heavy and fall rapidly, which suggests that r should appear upstairs. Which effect wins is not obvious, although after you have experience with these problems, you can make an educated guess: weight scales as r^3, a rapidly rising function r, whereas drag is probably proportional to a lower power of r. Weight usually wins such contents, as it does here, leaving r upstairs. So the terminal velocity also passes the r test.

Let's look at the dimensionless ratio in parentheses: $\rho_{obj}/\rho_{fl} - 1$. Without buoyancy the -1 disappears, and the terminal velocity would be
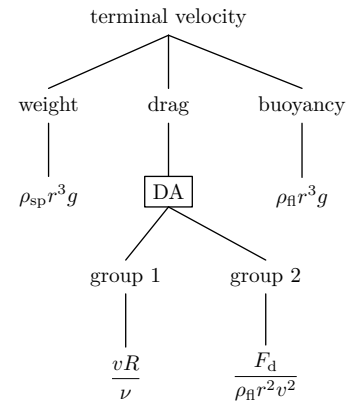
$$v \propto g \, \frac{\rho_{\text{obj}}}{\rho_{\text{fl}}}.$$

We retain the g in the proportionality for the following reason: The true solution returns if we replace g by an effective gravity g' where

$$g' \equiv g \left(1 - \frac{\rho_{\text{fl}}}{\rho_{\text{obj}}} \right).$$

So, one way to incorporate the effect of the buoyant force is to solve the problem without buoyancy but with the reduced g.

Check this replacement in two limiting cases: $\rho_{\text{fl}} = 0$ and $\rho_{\text{fl}} = \rho_{\text{obj}}$. When $\rho_{\text{obj}} = \rho_{\text{fl}}$ gravity vanishes: People, whose density is close to the density of water, barely float in swimming pools. Then g' should be zero. When $\rho_{\text{fl}} = 0$, buoyancy vanishes and gravity retains its full effect. So g' should equal g. The effective gravity definition satisfies both tests. Between these two limits, the effective g should vary linearly with ρ_{fl} because buoyancy and weight superpose linearly in their effect on the object. The effective g passes this test as well.

Another test is to imagine $\rho_{\text{fl}} > \rho_{\text{obj}}$. Then the relation correctly predicts that g' is negative: helium balloons rise. This alternative to using buoyancy explicitly is often useful. If, for example you forget to include buoyancy (which happened in the first draft of this chapter), you can correct the results later by replacing g with the g'.

If we carry forward the constants of proportionality, starting with the magic 6π in the Stokes drag and including the $4\pi/3$ that belongs in the weight, we find

$$v \sim \frac{2}{9} \, \frac{g r^2}{\nu} \left(\frac{\rho_{\text{obj}}}{\rho_{\text{fl}}} - 1 \right).$$

8.3.6 Conductivity of seawater

As an application of Stokes drag and a rare example of a realistic situation with low Reynolds numbers, let's estimate the electrical conductivity of seawater. Solving this problem is hopeless without breaking it into pieces. Conductivity σ is the reciprocal of resistivity ρ. (Apologies for the convention that overloads the density symbol with yet another meaning.) Resistivity, as its name suggests, is related to resistance R. Why have both ρ and R? Resistance is a useful measure for a particular wire, but not for wires in general because it depends on the diameter and cross-sectional area of the wire. It is not an intensive quantity. Before examining the relationship between resistivity and resistance, let's finish sketching the solution tree, leaving ρ as depending on R plus geometry. We can find R by placing a voltage V across a block of seawater and measuring the current I; then $R = V/I$.
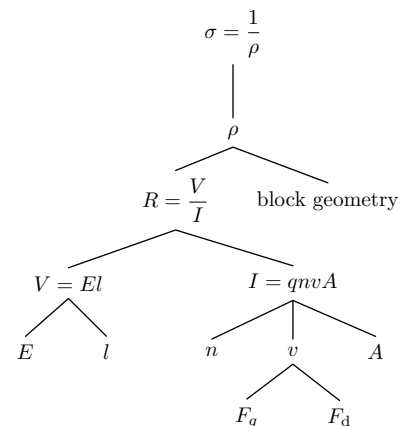
To find V or I we need a physical model. First, why does seawater conduct at all? Conduction requires the transport of charge, which is produced by an electric field. Seawater

is mostly water and table salt (NaCl). The ions that arise from dissolving salt can transport charge. The resulting current is

$$I = qnvA,$$

where A is the cross-sectional area of the block, q is the ion charge, n is the ion concentration, and v is its terminal speed.

To understand, and be able to rederive this formula, first check its dimensions. Current is charge per time. Is the right side also charge per time? Yes: q takes care of the charge; and vA has dimensions of $L^3 T^{-1}$ so nvA, which has dimensions of T^{-1}, takes care of the time.

As a second check, watch a cross-section of the block for a time Δt. How much charge flows in that time? The charges move at speed v, so all charges in block of width $v\Delta t$ and area A cross the cross-section. This block has volume $vA\Delta t$. The ion concentration is n, so the block contains $nvA\Delta t$ charges. If each ion has charge q, then the total charge on the ions is $Q = qnvA\Delta t$. It took a time Δt for this charge to flow, so the current is $I = Q/\Delta t = qnvA$. The terminal speed v depends on the applied force F_q and on the drag force F_d, just as for the falling marble but with an electrical force instead of a gravitational force. The result of this subdividing is the preceding map.

Now let's find expressions for the unknown nodes. Only three remain: ρ, v, and n. The figure illustrates the relation between ρ and R:

$$\rho = \frac{RA}{l}.$$
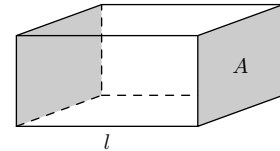
To find v we follow the same procedure as for the marble. The applied force is $F_q = qE$, where q is the ion charge and E is the electric field. The electric field produced by the voltage V is $E = V/l$, where l is the length of the block, so

$$F_q = \frac{qV}{l},$$

an expression in terms only of known quantities. The drag is Stokes drag. Equating this drag to the applied force gives the terminal velocity v in terms of known quantities:

$$v \sim \frac{qV}{6\pi\eta lr},$$

where r is the radius of the ion.

Only the number density n remains unknown. We estimate it after getting a symbolic result for σ, which you can do by climbing up the solution tree. First, find the current in terms of the terminal velocity:

$$I = qnvA \sim \frac{q^2 nAV}{6\pi\eta lr}.$$

Use the current to find the resistance:

$$R \sim \frac{V}{I} \sim \frac{6\pi\eta lr}{q^2 nA}.$$

The voltage V has vanished, which is encouraging: In most circuits the conductivity (and resistance) is independent of voltage. Use the resistance to find the resistivity:

$$\rho = R\frac{A}{l} \sim \frac{6\pi\eta r}{q^2 n}.$$

The expression simplifies as we rise up the tree: The geometric parameters l and A have also vanished, which is also encouraging: The purpose of evaluating resistivity rather than resistance is that resistivity is independent of geometry.

Use resistivity to find conductivity:

$$\sigma = \frac{1}{\rho} \sim \frac{q^2 n}{6\pi\eta r}.$$

Here q is the electron charge e or its negative, depending on whether a sodium or a chloride ion is the charge carrier, so

$$\sigma = \frac{1}{\rho} \sim \frac{e^2 n}{6\pi\eta r}.$$

To find σ still requires the ion concentration n, which we can find from the concentration of salt in seawater. This value I estimate with a kitchen-sink experiment: Add table salt to a glass of water until it tastes as salty as seawater. I just tried it. In a glass of water, I found that a teaspoon of salt tastes very salty, like drinking seawater. A glass of water may have a volume of $0.3\,\ell$ or a mass of $300\,\text{g}$. A flat teaspoon of salt has a volume of about $5\,\text{m}\ell$. For those who live in metric countries, a teaspoon is an archaic measure used in Britain and especially the United States, which has no nearby metric country to which it pays attention. A teaspoon is about $4\,\text{cm}$ long by $2\,\text{cm}$ wide by $1\,\text{cm}$ thick at its deepest point; let's assume $0.5\,\text{cm}$ on average. Its volume is therefore

$$\text{teaspoon} \sim 4\,\text{cm} \times 2\,\text{cm} \times 0.5\,\text{cm} \sim 4\,\text{cm}^3.$$

The density of salt is maybe twice the density of water, so a flat teaspoon has a mass of $\sim 10\,\text{g}$. The mass fraction of salt in seawater is, in this experiment, roughly $1/30$. The true value is remarkably close: 0.035. A mole of salt, which provides two charges per NaCl 'molecule', has a mass of $60\,\text{g}$, so

$$n \sim \frac{1}{30} \times \underbrace{1\,\text{g}\,\text{cm}^{-3}}_{\rho_{\text{water}}} \times \frac{2\,\text{charges}}{\text{molecule}} \times \frac{6 \cdot 10^{23}\,\text{molecules}\,\text{mole}^{-1}}{60\,\text{g}\,\text{mole}^{-1}}$$

$$\sim 7 \cdot 10^{20}\,\text{charges}\,\text{cm}^{-3}.$$

With n evaluated, the only remaining mysteries in the conductivity

$$\sigma = \frac{1}{\rho} \sim \frac{q^2 n}{6\pi\eta r}$$

are the ion radius r and the dynamic viscosity η.

Do the easy part first. The dynamic viscosity is

$$\eta = \rho_{\text{water}} \nu \sim 10^3 \, \text{kg} \, \text{m}^{-3} \times 10^{-6} \, \text{m}^2 \, \text{s}^{-1} = 10^{-3} \, \text{kg} \, \text{m}^{-1} \, \text{s}^{-1}.$$

Here I switched to SI (mks) units. Although most calculations are easier in cgs units – also known as God's units – than they are in SI units, the one exception is electromagnetism, which is represented by the e^2 in the conductivity. Electromagnetism is conceptually easier in cgs units – which needs no ghastly μ_0 or $4\pi\epsilon_0$, for example – than it is in SI units. However, the cgs unit of charge, the electrostatic unit, is unfamiliar. So, for numerical calculations, use SI units.

The final quantity required is the ion radius. A positive ion (sodium) attracts an oxygen end of a water molecule; a negative ion (chloride) attracts the hydrogen end of a water molecule. Either way, the ion, being charged, is surrounded by one or maybe more layers of water molecules. As it moves, it drags some of this baggage with it. So rather than use the bare ion radius you should use a larger radius to include this shell. But how thick is the shell? As an educated guess, assume that the shell includes one layer of water molecules, each with a radius of $1.5 \, \text{Å}$. So for the ion plus shell, $r \sim 2 \, \text{Å}$.
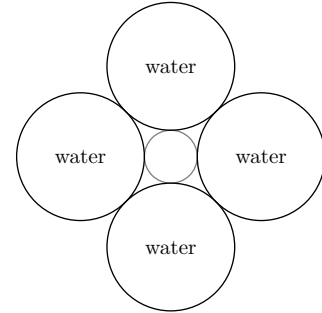
With these numbers, the conductivity becomes:

$$\sigma \sim \frac{\overbrace{(1.6 \cdot 10^{-19} \, \text{C})^2}^{e^2} \times \overbrace{7 \cdot 10^{26} \, \text{m}^{-3}}^{n}}{\underbrace{6 \times 3}_{6\pi} \times \underbrace{10^{-3} \, \text{kg} \, \text{m}^{-1} \, \text{s}^{-1}}_{\eta} \times \underbrace{2 \cdot 10^{-10} \, \text{m}}_{r}}.$$

You can do the computation mentally: *Take out the big part,* apply the *principle of maximal laziness,* and *divide and conquer* by first counting the powers of ten (shown in red) and then worrying about the small factors. Then *divide and conquer* again by counting the top and bottom contributions separately. The top contributes -12 powers of ten: -38 from e^2 and $+26$ from n. The bottom contributes -13 powers of ten: -3 from η and -10 from r. The division produces one power of ten.

Now account for the remaining small factors:

$$\frac{1.6^2 \times 7}{6 \times 3 \times 2}.$$

Slightly overestimate the answer by pretending that the 1.6^2 on top cancels the 3 on the bottom. Slightly underestimate the answer – and maybe compensate for the overestimate – by pretending that the 7 on top cancels the 6 on the bottom. After these lies, only 1/2 remains. Multiplying it by the sole power of ten gives

$$\sigma \sim 5 \, \Omega^{-1} \, \text{m}^{-1}.$$

Using a calculator to do the arithmetic gives $4.977 \ldots \, \Omega^{-1} \, \text{m}^{-1}$, which is extremely close to the result from mental calculation.

The estimated resistivity is

$$\rho \sim \sigma^{-1} \sim 0.2\,\Omega\,\mathrm{m} = 20\,\Omega\,\mathrm{cm},$$

where we converted to the conventional although not fully SI units of $\Omega\,\mathrm{cm}$. A typical experimental value for seawater at $T = 15\,°\mathrm{C}$ is $23.3\,\Omega\,\mathrm{cm}$ (from [15, p. **14**-15]), absurdly close to the estimate!

Probably the most significant error is the radius of the ion-plus-water combination that is doing the charge transport. Perhaps r should be greater than $2\,\text{Å}$, especially for a sodium ion, which is smaller than chloride; it therefore has a higher electric field at its surface and grabs water molecules more strongly than chloride does. In spite of such uncertainties, the continuum approximation produced more accurate results than it ought to.

At the length scale of a sodium ion, water looks like a collection of spongy boulders more than it looks like a continuum. Yet Stokes drag worked. It works because the important length scale is not the size of water molecules, but rather their mean free path between collisions. Molecules in a liquid are packed to the point of contact, so the mean free path is much shorter than a molecular (or even ionic) radius, especially compared to an ion with its shell of water.

The moral of this example, besides illustrating Stokes drag, is to have courage. Approximate first and ask questions later. Maybe the approximations are correct for reasons that you do not suspect when you start solving a problem. If you agonize over each approximation, you will never start a calculation, and then you will not find out that many approximations would have been fine...if only you had had the courage to make them.

8.3.7 Turbulent limit

We now compute drag in the other flow extreme: high-speed, or turbulent, flow. The example will be to compute the terminal speed of a raindrop. These results apply to most flows. For example, when a child rises from a chair, the airflow around her is high-speed flow, as you can check by computing the Reynolds number. Say that the child is $0.2\,\mathrm{m}$ wide, and that she rises with velocity $0.5\,\mathrm{m\,s^{-1}}$. Then

$$Re \sim \frac{vr}{\nu_{\mathrm{air}}} \sim \frac{0.5\,\mathrm{m\,s^{-1}} \times 0.2\,\mathrm{m}}{2\cdot 10^{-5}\,\mathrm{m^2\,s^{-1}}} \sim 5000.$$

Here viscosity of air is closer to

$$\nu_{\mathrm{air}} \approx 1.5 \cdot 10^{-5}\,\mathrm{m^2\,s^{-1}},$$

than to $2\cdot 10^{-5}\,\mathrm{m^2\,s^{-1}}$, but $2\cdot 10^{-5}\,\mathrm{m^2\,s^{-1}}$ easily combines with the $0.2\,\mathrm{m}$ in the numerator to allows us to do the calculation mentally. Using either value for the viscosity, the Reynolds number is much larger than unity, so the flow is turbulent. Larger objects, such as planes, trains, and automobiles, create turbulence even when they travel even more slowly than the child. In short, most fluid flow around us is turbulent flow.

To begin the analysis, we assume that a raindrop is a sphere. It is a convenient lie that allows us to reuse the general results of **Section 8.3.3** and specialize to high-speed flow. At high speeds (more precisely, at high Reynolds number) the flow is turbulent. Viscosity – which affects only slow flows but does not directly influence the shearing and whirling of turbulent flows – becomes irrelevant. Let's see how much we can understand about turbulent drag knowing only that turbulent drag is nearly independent of viscosity.

Turbulence is perhaps the main unsolved problem in classical physics. However, you can still understand a lot about drag using dimensional analysis plus a bit of physical reasoning; we do not need a full understanding of turbulence. The world is messy: Do not wait for a full understanding before you analyze or estimate.

In the roadmap for low Reynolds number, the viscosity appears only in the first group. Because turbulent drag is independent of the viscosity, the viscosity disappears from the results and therefore so does that group. This argument is glib. More precisely, remove ν from the list of variables and search again for dimensionless groups. The remaining four variables, shown in the table, result in one

Var	Dim	What
F_d	MLT^{-2}	drag force
ρ_{fl}	ML^{-3}	fluid density
r	L	object radius
v	LT^{-1}	terminal velocity

dimensionless group, which is the second group from the old roadmap.

So the Reynolds number, which was the first group, has disappeared from the analysis. But why is drag at high speeds independent of Reynolds number? Equivalently, why can we remove ν from the list of variables and still get the correct form for the drag force? The answer is not obvious. The explanation of the Reynolds number as a ratio of two speeds v and V provides a partial answer. A natural length in this problem is r; we can use r to transform v and V into times:

$$\tau_v \equiv \frac{r}{v},$$

$$\tau_V \equiv \frac{r}{V} \sim \frac{r^2}{\nu}.$$

Note that $Re \equiv \tau_V/\tau_v$. The quantity τ_v is the time that fluid takes to travel around the sphere (apart from constants). Kinematic viscosity is ν/ρ, but its most important interpretation is as the diffusion coefficient for momentum. So the time for momentum to diffuse a distance x is

$$\tau \sim \frac{x^2}{\nu}.$$

This result depends on the mathematics of random walks; you can increase your confidence in it here, without understanding the theory of random walks, by checking that it has valid dimensions. And it has: Each side is a time.

So τ_V is the time that momentum takes to diffuse around an object of size r, such as the falling sphere in this problem. If $\tau_V \ll \tau_v$ – in which case $Re \ll 1$ – then momentum diffuses before fluid travels around the sphere. Momentum diffusion equalizes velocities, if it has time, which it does have in this low-Reynolds-number limit. Momentum diffusion

therefore prevents flow at the front from being radically different from the flow at the back, and thereby squelches any turbulence. In the other limit, when $\tau_V \gg \tau_v$ or $Re \gg 1$ – momentum diffusion is outraced by fluid flow, so the fluid is free to shred itself into a turbulent mess. Once the viscosity is low enough to allow turbulence, its value does not affect the drag, which is why we can ignore it for $Re \gg 1$. Here $Re \gg 1$ means 'large enough so that turbulence sets in', which happens around $Re \sim 1000$. A more complete story, which we discuss as part of boundary layers in **Section 9.4**, slightly corrects this approximation. However, it is close enough for our purposes here.

Here the important point is that the viscosity vanishes from the analysis and so does group 1. Once it disappears, the dimensionless group that remains is

$$G_2 = \frac{F_d}{\rho_{fl} r^2 v^2}.$$

Because it is the only group, the solution is

$$G_2 = \text{dimensionless constant},$$

or

$$F_d \sim \rho_{fl} r^2 v^2.$$

This drag is for a sphere. What about other shapes, which are characterized by more parameters than a sphere is? So that the drag force generalizes to more complex shapes, we express it using the cross-sectional area of the object. Here $A = \pi r^2$, so

$$F_d \sim \rho_{fl} A v^2.$$

This conventional choice has a physical basis. As an object moves, the mass of fluid that it displaces is proportional to its cross-sectional area:
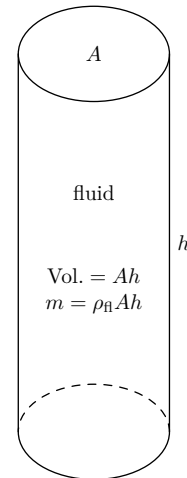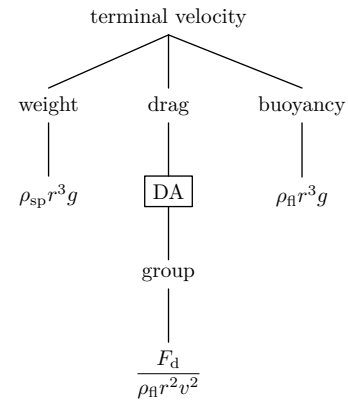
$$m_{fl} = \rho_{fl} A h.$$

The fluid is given a speed comparable to v, so the fluid's kinetic energy is

$$E_K \sim \frac{1}{2} m_{fl} v^2 \sim \frac{1}{2} \rho_{fl} A h v^2.$$

If all this kinetic energy is dissipated by drag, then the drag force is E_K / h or

$$F_d \sim \frac{1}{2} \rho_{fl} A v^2.$$

In this form with the factor of 1/2, the constant of proportionality is the **drag coefficient** c_d.

Like its close cousin f from the dimensionless drag force, the drag coefficient is a dimensionless measure of the drag force. It depends on the shape of the object – on how streamlined it is. The table lists c_d for various shapes (at high Reynolds number). The drag coefficient, being proportional to the function $f(Re)$ in the general solution, also depends on the Reynolds number. How-ever, using the reasoning that the flow at high Reynolds number is indepen-dent of viscosity, the drag coefficient should also be independent of Reynolds number. Using the drag coefficient instead of f (which implies using cross-sectional area instead of r^2), the turbulent drag force becomes

Object	c_d
Sphere	0.5
Cylinder	1.0
Flat plate	2.0
Car	0.4

$$F_d = \frac{1}{2}c_d\rho_{fl}v^2 A.$$

So we have an expression for the turbulent drag force. The weight and buoyant forces are the same as in the viscous limit. So we just need to redo the analysis of the viscous limit but with the new drag force. Because the weight and buoyant forces contain r^3, we return to using r^2 instead of A in the drag force. With these results, the terminal velocity v is given by

$$\underbrace{\rho_{fl}r^2v^2}_{F_d} \sim \underbrace{g(\rho_{obj} - \rho_{fl})r^3}_{F_g - F_b},$$

so

$$v \sim \sqrt{gr\left(\frac{\rho_{obj}}{\rho_{fl}} - 1\right)}.$$

Pause to sanity check this result: Are the right variables upstairs and downstairs? We consider each variable in turn.

- ρ_{fl}: The terminal velocity is smaller in a denser fluid (try running in a swimming pool), so ρ_{fl} should be in the denominator.

- g: Imagine a person falling on a planet that has a gravitational force stronger than that of the earth. Gravity partially determines atmospheric pressure and density. Holding the atmospheric density constant while increasing gravity might be impossible in real life, but we can do it easily in a thought experiment. The drag force then does not depend on g, so gravity increases the terminal speed without opposition from the drag force: g should be upstairs.

- ρ_{obj}: Imagine a raindrop made of (very) heavy water. Relative to a standard raindrop, the gravitational force increases while the drag force remains constant, as shown using the fluid-is-a-computer argument in ??sec:drag-force-DA. So ρ_{obj} should be upstairs.

- r: To determine where the radius lives requires a more subtle argument. Increasing r increases both the gravitational and drag forces. The gravitational force increases as r^3

whereas the drag force increases only as r^2. So, for larger raindrops, their greater weight increases v more than their greater drag decreases v. Therefore r should be live upstairs.

- ν: At high Reynolds number viscosity does not affect drag, at least not in our approximation. So ν should not appear anywhere.

The terminal velocity passes all tests.

Now we can compute the terminal velocity. The splash spots on the sidewalk made by raindrops in a recent rain have $r \sim 0.3\,\text{cm}$. Since rain is water, its density is $\rho_{\text{obj}} \sim 1\,\text{g cm}^{-3}$. The density of air is $\rho_{\text{fl}} \sim 1\,\text{kg m}^{-3}$, so $\rho_{\text{fl}} \ll \rho_{\text{obj}}$: Buoyancy is therefore not an important effect, and we can replace $\rho_{\text{obj}}/\rho_{\text{fl}} - 1$ by $\rho_{\text{obj}}/\rho_{\text{fl}}$. With this simplification and the estimated numbers, the terminal velocity is:

$$
v \sim \left(\underbrace{1000\,\text{cm s}^{-2}}_{g} \times \underbrace{0.3\,\text{cm}}_{r} \times \underbrace{\frac{\overbrace{1\,\text{g cm}^{-3}}^{\rho_{\text{obj}}}}{\underbrace{10^{-3}\,\text{g cm}^{-3}}_{\rho_{\text{fl}}}} \right)^{1/2} \sim 5\,\text{m s}^{-1},
$$

or 10 mph.

This calculation assumed that $Re \gg 1$. Check that assumption! You need not calculate Re from scratch; rather, scale it relative to a previous results. As we worked out earlier, a child ($r \sim 0.2\,\text{m}$) rising from her chair ($v \sim 0.5\,\text{m s}^{-1}$) creates a turbulent flow with $Re \sim 5000$. The flow created by the raindrop is faster by a factor of 10, but the raindrop is smaller by a factor of roughly 100. Scaling the Reynolds number for the child gives

$$
Re \sim \underbrace{Re_{\text{child}}}_{5000} \times \underbrace{\left(\frac{v_{\text{drop}}}{v_{\text{child}}} \right)}_{10} \times \underbrace{\left(\frac{r_{\text{drop}}}{r_{\text{child}}} \right)}_{0.01} \sim 500.
$$

This Reynolds number is also much larger than 1, so the flow produced by the raindrop is turbulent, which vindicates the initial assumption.

Now that we have found the terminal velocity, let's extract the pattern of the solution. The order that we followed was *assume*, *derive*, *calculate*, then *check*. This order is more fruitful than is the simpler order of *derive* then *calculate*. Without knowing whether the flow is fast or slow, we cannot derive a closed-form expression for F_{d}; such a derivation is probably beyond present understanding of fluids and turbulence. Blocked by this mathematical Everest, we would remain trapped in the *derive* box. We would never determine F_{d}, so we would never realize that the Reynolds number is large (the *assume* box); however, only this assumption makes it possible to eliminate ν and thereby to estimate F_{d}. The moral: Assume early and often!
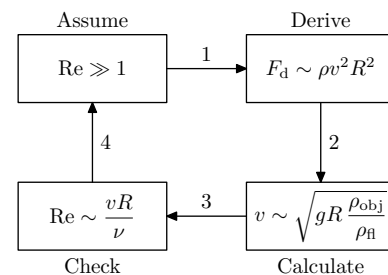
8.3.8 Combining solutions from the two limits

You know know the drag force in two extreme cases, viscous and turbulent drag. The results are repeated here:

$$F_d = \begin{cases} 6\pi\rho_{fl}\nu v r & \text{(viscous),} \\ \frac{1}{2}c_d\rho_{fl}Av^2 & \text{(turbulent).} \end{cases}$$

Let's compare and combine them by making the viscous form look like the turbulent form. Compared to the turbulent form, the viscous form lacks one power of r and one power of v but has an extra power of ν. A combination of variables with a similar property is the Reynolds number rv/ν. So multiply the viscous drag by a useful form of unity:

$$F_d = \underbrace{\left(\frac{rv/\nu}{Re}\right)}_{1} \times \underbrace{6\pi\rho_{fl}v\rho_{fl}\nu r}_{F_d} = \frac{1}{Re}\,6\pi\rho_{fl}v^2r^2 \quad \text{(viscous).}$$

This form, except for the 6π and the r^2, resembles the turbulent drag Fortunately $A = \pi r^2$ so

$$F_d = \frac{6}{Re}\,\rho_{fl}v^2A \quad \text{(viscous),}$$

With

$$c_d = \frac{12}{Re} \quad \text{(viscous),}$$

the turbulent drag and this rewritten viscous drag for a sphere have the same form:

$$F_d = \frac{1}{2}\rho_{fl}Av^2 \times \begin{cases} \dfrac{12}{Re} & (Re \ll 1), \\[2mm] 0.5 & (Re \gg 1). \end{cases}$$

At high Reynolds number the drag coefficient remains constant. For a sphere, that constant is $c_d \sim 1/2$. If the low-Reynolds-number approximation for c_d is valid at sufficiently high Reynolds numbers, then c_d would cross 1/2 near $Re \sim 24$, where presumably the high-Reynolds-number approximation takes over. The crossing point is a reasonable estimate for the transition between low- and high-speed flow. Experiment or massive simulation are the only ways to get a more accurate result. Experimental data place the crossover near $Re \sim 5$, at which point $c_d \sim 2$. Why can't you calculate this value analytically? If a dimensionless variable, such as the Reynolds number, is close to unity, calculations become difficult. Approximations that depend on a quantity being either huge or tiny are no longer valid. When all terms in an equation are roughly of the same magnitude, you cannot get rid of any term without making large errors. To get results in these situations, you have to do honest work: You must do experiments or solve the Navier–Stokes equations numerically.