BASICS: Biophysics - A Step-by-step Introduction to Concepts for Students

Lesson Plan: Aerosols & Infection

Background

Aerosols are tiny particles or droplets suspended in a gas, such as air. There are millions of particles or droplets in the air we breathe. Aerosols are produced by naturally occurring processes such as rain, waterfalls, dust storms and volcanic eruptions. They can also be formed by human activities such as boiling water, opening a can of soda, turning on a water faucet, or taking a shower. Finally, people create aerosols when they cough, sneeze, talk, or even breathe – think about how you can "see your breath" in the winter when you go outside into the cold. This happens when you exhale and the small water droplets in your warm breath condense in the cold air, forming a cloud, or an aerosol. Because of the small size of water droplets or particles in aerosols, they float easily through air and follow the direction of air flow. The small droplets or particles in aerosols undergo **diffusion** – rapid back and forth movement – at rates that we can estimate, but they travel through air by **convection**, the bulk movement or transport of substances in a fluid, like air. However, larger droplets or particles of greater mass will fall to the ground due to gravity.

Aerosols can play an unintended role in spreading infections from bacteria and viruses that can cause you to get sick. In this lesson plan, we will demonstrate how viruses, such as the SARS-Cov-2 virus that causes COVID-19, can spread disease. Viruses are small particles that can float or move in air in aerosols. People become infected by breathing in virus which then make more copies of themselves inside cells of the infected person. After the virus has made many copies of itself by infecting and damaging many cells of the body, the infected person usually begins to show symptoms of the disease.

Infected people can spread virus through sneezes, coughs and even talking. Virus is expelled from the infected person's body in small water droplets that can float or move in air. These droplets can infect other people when they breathe them in, spreading the disease. The larger virus-containing droplets sink due to gravity and land on surfaces. The virus in these droplets can infect others when they touch the surface, transferring virus to their hands and then to their nose and mouth.

Objectives & Grade Level

Demonstrate how aerosols travel through air and estimate mass of droplets that fall down onto surfaces. Appropriate for middle school to high school science classes; see notes for advanced students.

Materials

- Water
- Food coloring (e.g., McCormick Assorted Food Colors)
- Atomizer, spray bottle or spritzer (**Fig. 1**)
- White printer paper
- Mask: Paper towel, Rubber bands (2)

Fig. 1 Atomizer

Atomizer (**left**); atomizer opening (**right**).

Preparation of Materials

Preparation of Colored Water (Experiments 1 and 2*)*

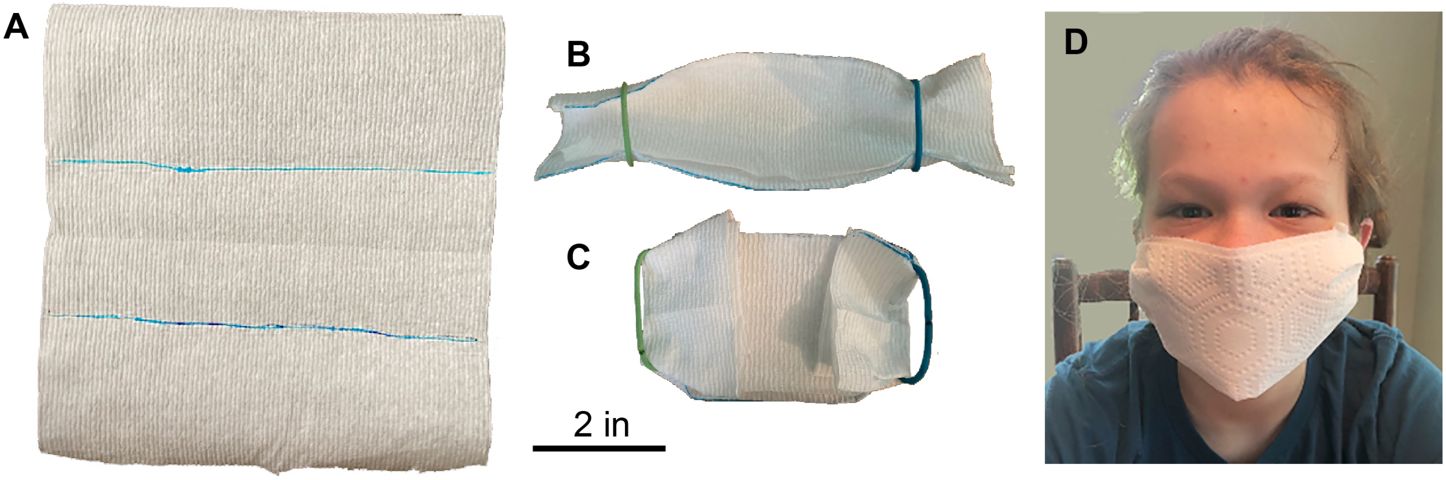
1. Measure ¼ cup (~60 *mL*) of water into a container.
2. Add 8 drops of food coloring to the water – we used Red for our experiments – and swirl to mix. Darker colored water is easier to detect in these experiments.
3. Pour colored water into atomizer, spray bottle or spritzer.

Face Mask (Experiment 2)

We made a face mask from a paper towel for this experiment so we could determine the effect of the mask on preventing the transmission of the aerosol of colored water.

1. Take a paper towel square and fold it into thirds (blue lines, **Fig. 2A**).
2. Slide a rubber band onto each end of the folded paper towel (**Fig. 2B**), then fold the paper towel ends toward the center (**Fig. 2C**).
3. Fit the mask over your nose and mouth, holding it in place by securing the rubber bands around your ears (**Fig. 2D**, *with permission*). Now you have a mask!

Fig. 2 Face Mask

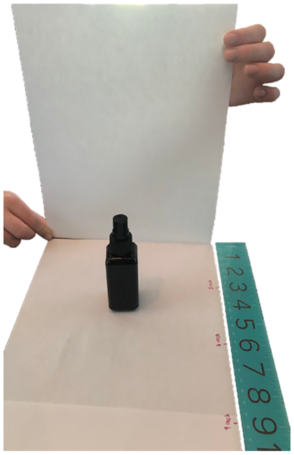


Procedure

Experiment 1: Aerosol demonstration

1. Place printer paper sheets flat on a table in front of the atomizer and have a friend or family member hold a sheet of paper vertical to the table (**Fig. 3**). Make a note of the distance of the atomizer to the vertical paper.
2. Using a cell phone camera, take a photo of each piece of paper to record the background before the experiment.

Fig. 3



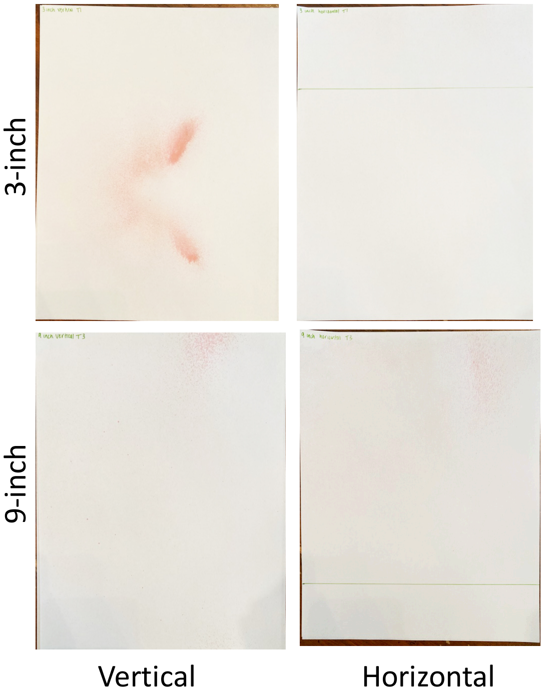
3. Press down on the atomizer with as much pressure as it will allow, spraying the water across the table towards the vertical sheet of paper.
4. Take a photo of the horizontal and vertical paper sheets after spraying to record the distribution of water droplets from the aerosol.
   a. *What is the distribution of water droplets on the paper sheets?*

      In our experiments, we observed many tiny spots on the vertical paper in an irregular, somewhat circular distribution (see **Fig. 4**, top left). The distribution can differ using a different atomizer.

   b. *Are the distributions different for the horizontal paper sheets, compared to the vertical paper?*

      Yes! We observed a large area of small spots on the vertical paper and many fewer spots on the horizontal paper (**Fig. 4**, top right).
5. Now spray the colored water from two different distances away from the vertical paper and observe what happens to the distribution of spots. For example, try spraying the atomizer from 3 inches and 9 inches away from the vertical paper.

Fig. 4



a. *How does the aerosolized droplet distribution change when you move the atomizer farther away from the vertical paper?*

The distribution of spots on the vertical paper becomes larger when the atomizer is farther away (**Fig. 4**, bottom left). This occurs because the forward movement of the droplets slows due to air resistance and the droplets begin to fall due to gravity; the droplets can also diffuse in air before they land on the vertical paper (see **Notes**). The horizontal paper sheet shows a larger distribution of spots because more droplets fall because of the slowing down of their forward velocity and the effects of gravity (**Fig. 4**, bottom right).

b. *What do you think would happen if we changed the size of the hole in the water atomizer? Or, if we changed the pressure used to create the aerosol?*

If there is a larger hole, the size of the droplets produced by the atomizer would be larger and more of the droplets would fall onto the horizontal paper. If we spray with lower pressure, the droplets would again be larger and would not travel as far, increasing the distribution of spots on the horizontal paper.

Experiment 2: Aerosol with mask

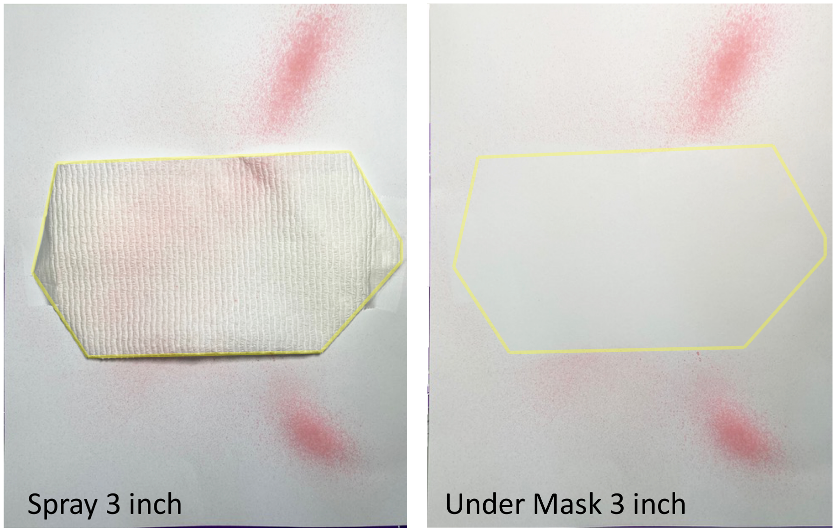
1. For safety, remove the paper towel mask from your face for the experiment.
2. Have a friend or family member hold a sheet of paper vertical to a table (see **Fig. 3**) and take a photo for a

background control, then have him/her hold the mask against the paper with the outside facing out (outside refers to the side that would not touch your face if you were wearing the mask).

3. Spray the colored water onto the mask and vertical paper from a distance of 3 inches. Remove the mask and take a photo of the paper to see how many of the aerosolized colored droplets went through the mask.
    a. *Are there more or fewer spots on the paper that was covered by the mask than the region without the mask? What about the paper covered by the mask compared to the vertical paper sprayed from 3 inches in Experiment 1? How can you explain this?*

       There are fewer spots on the vertical paper that was protected by the mask than the vertical paper in Experiment 1 (**Fig. 4**) because the mask absorbed the aerosolized droplets so that they did not go through onto the paper. If the droplets had contained virus and you were wearing the mask, the virus would not have gone through the mask and would not be breathed in.

Fig. 5



Quantitation of Aerosol Droplets on Paper Sheets

Procedures

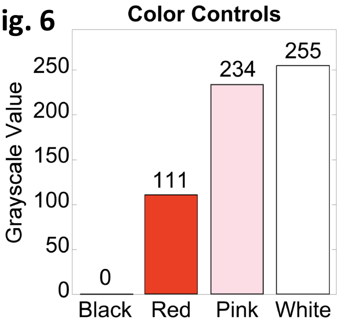
- We used the program FIJI (available at https://fiji.sc) to measure the aerosol droplets that landed on the paper sheets. After opening photos of the paper sheets in FIJI, we changed the photos with red colored spots to 8-bit *grayscale* images to standardize the measurements. We then measured the grayscale values of the paper sheets before and after spraying:

1. Go to File > Open and select the photo to open
2. Go to > Image > Type > *8-bit* to change the photo from RGB to 8-bit grayscale.
3. Go to Analyze > Set Measurements, select *Area*, *Min & max gray value* and *Mean gray value*, set decimal places to 0, and click OK.
4. Select the rectangle (box) tool on the toolbar and draw a box on the image. Go to Analyze > Measure. Results for *Area*, *Mean*, *Min and Max* grayscale values of the boxed region will appear in a new window.

- For an 8-bit image, the shade of gray of each *picture element* or **pixel** that makes up the image is given by an 8-place number consisting of 0's and 1's. Since each position in the 8-place number can be either 0 or 1, there are 2^8 = 256 different shades of gray. The smallest and largest numbers, 0000000 and 11111111, are assigned as black or white.

- For quantitation of our aerosol experiments, we first measured images consisting of blocks of single colors (white, pink, red, black) after converting the images to 8-bit, to determine their grayscale values. The measurements in FIJI gave Black=0 (or 00000000 for an 8-bit image) and White=255 (or 11111111 for an 8-bit image) with Red=111 and Pink=234 (**Fig. 6**). This means that lighter colors such as White and Pink have higher grayscale values in FIJI than darker colors such as Black and Red. That is, the grayscale values for the sprayed papers will *decrease* with greater numbers of red droplets that have landed and formed spots.

Fig. 6



- We then measured the minimum, maximum and mean grayscale values of the papers from our experiments before and after spraying. Since the minimum grayscale values correspond to the darkest red spots on each paper, we used the minimum (Min) grayscale values for each paper as a measure of the largest number of droplets that had landed on the paper. We compared the Min values before and after spraying the aerosol to make certain that the paper itself was not giving low grayscale values. We used the same methods to determine the effect of the mask in protecting the paper from the dye spots.

Measurements

For each trial, we measured the entire blank page before spraying (background before spraying), together with the largest area possible for the region of the paper without droplets after spraying (background after spraying) and the region of the paper on which the droplets had landed after spraying, excluding lines and writing on the paper. We then calculated the average Min grayscale values and experimental error (standard error of the mean, *SEM*; standard deviation, *SD*; see *BASICS: Lesson Plan on Experimental Error*). Because the *SEMs* for the two backgrounds (before and after spraying) were overlapping or close to one another for the 3 inch (*n*=3) and 9 inch (*n*=3) experiments, we calculated a single average background for each set of experiments. For consistency, we also calculated a single background for the mask experiment, although the background before spraying (104±2.19, *mean*±*SEM*, *n*=3) was significantly different from the background after spraying (143±16.8, *n*=3), probably because of differences in experimental conditions, e.g., room lighting when the background control photos and photos after spraying were taken.

The plots and photos of the aerosol experiments show that there were more aerosol droplets on the 3 inch vertical papers than the horizontal papers, while the 9 inch experiments showed approximately the same distribution of spots on the vertical and horizontal papers, differing significantly from the 3 inch experiments (**Fig. 4** & **Fig. 7**, gray bars).

Fig. 7

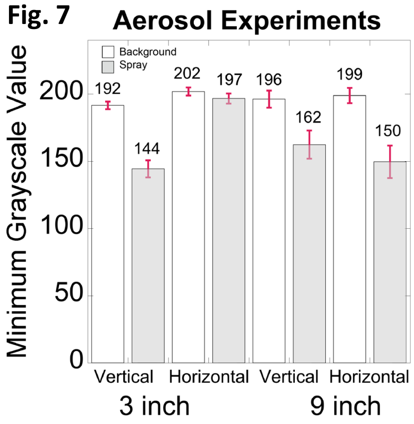
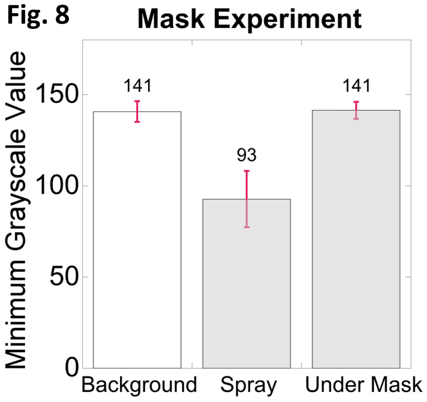


Fig. 8



The mask experiment shows that the sprayed mask has droplets on the outside, but that the region of the paper covered by the mask was protected from the aerosol droplets (**Fig. 5** & **Fig. 8**, gray bars). This experiment demonstrates that the mask is an effective way to block the aerosolized droplets from landing on the paper.

Conclusions

These experiments show that 1) the distribution of aerosolized droplets changes depending on the distance from the aerosol source. When we moved the atomizer farther away from the vertical paper, the distribution of the droplets was broader (**Fig. 4**). 2) The droplets that fell due to gravity and landed on the horizontal paper increased in the 9 inch spray experiments compared to the 3 inch experiments (**Fig. 4** & **Fig. 7**). There were no visible spots on the horizontal paper sheets after the atomizer had been sprayed at 3 inches, but there were many spots after the atomizer had been sprayed at 9 inches. Because of the greater distance the droplets had to travel, more of them fell before reaching the vertical paper. 3) No aerosol droplets went through our paper towel mask onto the vertical paper, although the droplets landed on places that the mask did not cover (**Fig. 5** & **Fig. 8**).

These experiments help us understand how to limit the spread of viruses such as SARS-CoV-2, which causes COVID-19. First, aerosols containing virus that are produced by coughs or sneezes of infected persons will spread out and become more diffuse with increased distance to another person (Bromage, 2020). Second, masks can greatly reduce the virus-containing aerosol droplets that come into contact with a person, which can enter the body through the nose and mouth. Since these two areas are otherwise unprotected against the virus, it is very important to prevent the spread of viral infection by wearing a mask (Prather et al., 2020). Medical masks, cotton masks and even the paper towel masks used in our experiments will help reduce the spread of the virus. Thus, keeping other potentially infected persons at a distance and wearing a mask are two effective ways of preventing the spread of viral infections such as COVID-19.

Notes

The water droplets in our aerosols are propelled forward from the atomizer opening because of the force we used to create the aerosol by pressing down on the atomizer top. The droplets slow down because of air resistance and fall because of gravity. The droplets can also diffuse in air before landing on the horizontal or vertical paper sheets. We estimated diffusion rates of the droplets in air and the size of the droplets that fall due to gravity, as shown below.

Advanced topic 1 The Stokes-Einstein diffusion equation models particle diffusion in a given medium. We used the Stokes-Einstein equation to calculate a diffusion coefficient for the aerosolized droplets to estimate how rapidly the droplets diffuse in air. The equation is given as follows:

$$D = \frac{kT}{6\pi\eta R}$$

D, Diffusion coefficient of droplets ($\frac{cm^2}{s}$)
k, Boltzman constant, $1.38065 \times 10^{-16}\ \frac{g*cm^2}{K*s^2}$
T, absolute temperature (K)
η, solvent viscosity ($\frac{g}{cm*s}$)
R, hydrodynamic radius of droplets (cm)

The temperature at which our experiments were performed is T= 25°C=~298°K. Viscosity, η= ~$1.81\times 10^{-4}\,\frac{g}{cm*s}$, for air at 25°$C$. Using these values, we determined the relationship between the diffusion coefficient and the hydrodynamic radius of the droplets in the aerosol as follows:

$$D = \frac{1.38065\times 10^{-16}\times 298}{6\,\pi\times 1.81\times 10^{-4}\times R} = \frac{4.1144\times 10^{-14}}{1.09\times 10^{-3}\ \times \pi\ R}\quad cm^2/s$$

We assumed that the droplets in the aerosol in each experiment are smaller than the smallest droplets that fell onto the horizontal paper. We estimated the hydrodynamic radius, R, of the smallest droplets sprayed by the atomizer at 9 inches from the vertical paper by measuring the diameter of the smallest spots on the horizontal paper and dividing by 2 to find the radius. The average radius of the smallest spots was 0.0833±0.0258 *mm* (*mean±SD*, *n*=6). We hypothesized that the spots on the paper corresponded to flattened spherical droplets with an area related to the volume of the original droplets. To determine the relationship between the spot area and original droplet volume, we made spots of colored water of different volumes (2, 4, 8 μl) on the same paper as we used in the aerosol spray experiments and measured the spot diameter, then we calculated the spot radius and area. By plotting the spot area *vs* drop volume, we found that the area of the spots, A (cm^2), was proportional to 0.036337 x the volume, V (μl), of the original drops. From the average radius above of the smallest spots, 0.0833±0.0258 *mm*, we calculated the area of the smallest spots, $A=\pi r^2=\pi(0.00833\ cm)^2=0.000218\ cm^2$ and divided by 0.036337 to find the volume of the original droplets, V=0.00600 μl = 0.00600 x 10^{-3} cm^3. Assuming the droplets are spheres, $V=4/3\ \pi r^3$= 0.00600 x 10^{-3} cm^3 and r=0.0113 *cm*. We used this value of r for the hydrodynamic radius of the smallest droplets that landed on the vertical paper in our 9 inch aerosol spray experiment, R=0.0113 *cm*. We assumed that droplets smaller than this remained suspended in air and could diffuse in air as aerosols, and that the hydrodynamic radius of these droplets in aerosols is $R < 0.0113$ *cm.*

The diffusion coefficient, D, for the aerosol droplets that remain suspended in air and diffuse is given by the following inequality, which accounts for values of $R < 0.0113$ *cm* and is consistent with increased D as droplet size decreases:

$$D > \frac{4.1144\times 10^{-14}}{1.09\times 10^{-3}\ \times\ 0.0113\,\pi}\quad cm^2/s$$

$$D > 1.06\times 10^{-9}\quad cm^2/s$$

Does the radius of the smallest spots on the vertical paper change depending on the distance at which you sprayed the aerosol?

How does increasing the spraying distance from the vertical paper change the value of D for the droplets that are smaller than the smallest droplets that landed on the paper?

NB: The value of D may differ with your atomizer in your experiments compared to ours.

The calculation above gives the diffusion coefficient, D, for the droplets that remained suspended in air as aerosols and diffuse. These droplets consist of a wide range of sizes that are smaller than the smallest droplets of average radius, r=0.0113 *cm*, that fell onto the paper. To estimate the distance that the aerosol droplets diffuse, we calculated the diffusion coefficient, D, for droplets that were 10 times, 100 times and 1000 times smaller in size than the smallest droplets that fell onto the horizontal paper. Note that *D* increases as droplet size decreases. We obtained the following values for *D*:

Droplets 10x smaller	R=0.00113 *mm*	D=1.06×10^{-8} cm^2/s
Droplets 100x smaller	R=0.000113 *mm*	D=1.06×10^{-7} cm^2/s
Droplets 1000x smaller	R=0.0000113 *mm*	D=1.06×10^{-6} cm^2/s

The distance that the droplets of different sizes travel in air by diffusion can be estimated using the Einstein-Smoluchowski diffusion equation. For our estimates, we use the derivation for 3D diffusion (Berg 1983):

$$x^2 = 6Dt$$

x, distance (*cm*)
D, diffusion coefficient (cm^2/s)
t, time (*s*)

For our estimates, we calculated the distance traveled in 10 *min*=600 *s* by the droplets that remain suspended in air:

Droplets 10x smaller:
$$x^2 = 6(1.06 \times 10^{-8})(600)\ cm^2$$
$$x = 6.18 \ \times 10^{-3}\ cm$$

Droplets 100x smaller:
$$x^2 = 6(1.06 \times 10^{-7})(600)\ cm^2$$
$$x = 1.95 \ \times 10^{-2}\ cm$$

Droplets 1000x smaller:
$$x^2 = 6(1.06 \times 10^{-6})(600)\ cm^2$$
$$x = 6.18 \ \times 10^{-2}\ cm$$

The distances traveled by the droplets by diffusion in 10 *min* are very small, less than a *cm*. Even the droplets that are 1000x smaller than the smallest droplets that fell onto the horizontal paper travel much less than 1 *cm* in 10 *min* by diffusion. This means that the droplets in the aerosol spread out due to diffusion, but diffusion in air does not contribute significantly to the distance traveled by the droplets before they land on the vertical paper. Instead, the air currents created by the atomizer when the droplets are produced cause the droplets in the aerosol to travel through the air by convection.

Advanced topic 2 We calculated how large a droplet must be to fall due to gravity in our experiments and how quickly the droplets fall. The droplets fall because they are heavier than air resistance. We assumed that droplets fall if they are equal to or greater in mass than the smallest droplets that fell onto the horizontal sheet of paper.

Newton's Second Law of Motion states that force acting on an object results in acceleration that is dependent on the mass of the object. For objects falling due to gravity, this is given by the equation:

$$F_g = mg$$

F_g, Force of gravity (N)
m, mass of the object (kg)
g, acceleration of gravity= 9.8 m/s^2

A droplet in our experiments has a mass sufficient to fall when F_g is equal to air resistance, or drag. The equation modeling drag is as follows:

$$F_d = \frac{1}{2} C_d V^2 \rho A$$

F_d, Force of drag (N)
C_d, Drag coefficient
V, velocity of droplet (m/s)
ρ, density of air (kg/m^3)
A, cross sectional area of droplet (m^2)

We assumed that the droplets produced by our atomizer are spherical. This allowed us to let $C_d = 0.47$ for a spherical object. The density of air is ~1.2 kg/m^3. The cross-sectional area of the droplet can be approximated using the formula for a circle, $A = \pi r^2$. We used our corrected estimate of r=0.0113 cm for the radius of the smallest spots on the horizontal paper in our 9 inch aerosol experiment, as described above in *Advanced topic 1*. The velocity of the droplets that fell onto the horizontal paper can be estimated from acceleration of gravity and time by measuring the height of the hole in the atomizer. This height, $h = ½ gt^2$, where t is the time required for droplets to land on the horizontal paper. For our atomizer, h=11.561±0.0111 cm (*mean±SD*, n=6; **Fig. 1**). After solving for t=0.154 s, we estimated the velocity of the smallest droplets that fell onto the horizontal paper from $V = gt$=1.51 m/s.

The mass of the smallest droplets that fell onto the horizontal paper is then given by

$$mg = \frac{1}{2} \times .47 \times (gt)^2 \times 1.2 \times \pi r^2 \;\; kg\, m/s^2$$

We solved for m=2.63 x 10^{-9} kg=2.63 μg. Droplets that are equal to or greater in mass will fall and land on the paper due to gravity and those of smaller mass will remain suspended in air as an aerosol.

Note that our estimates of the smallest drops that fell are limited by our measurements of the smallest spot diameters on the paper, which were measured with a centimeter ruler marked in *mm* using a small magnifying lens; a cell phone camera can be used to magnify the spots on the paper for greater accuracy.

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