# Lecture 1: Air and Air Pressure

The purpose of this lecture is to review or introduce the properties of the air, air pressure, and some basic physics concepts which we will need repeatedly in this course.

On the large scale, air is described by

- temperature
- density
- velocity
- pressure

It might help to think about these, to see how they arise from the microscopic description in terms of individual air molecules.

Air is made up of a vast number of tiny, freely flying atoms and molecules. These are

- Tiny–typically $3 \times 10^{-10} = 0.0000000003$ meters across, 1/200000 the width of a hair.
- Fast moving–each in a random direction, typically around 450 m/s = 1600 km/h, twice as fast as an airplane and nearly as fast as a bullet.
- Packed together loosely, around $3 \times 10^{-9} = 0.000000003$ meters apart from each other.
- Huge in number. 1 liter of air has about $3 \times 10^{22}$ molecules in it.

Because they are smaller than their separation, they fly a (comparatively) long ways between collisions, roughly $10^{-7} = 0.0000001$ meters. But that is still tiny, only 1/500 of the thickness of a hair. That means that each separate air molecule "runs back and forth" very fast but never gets anywhere.

Since there are so many air molecules, what we feel is the total effect of a huge number, that is, an average. The relation between the properties of the air molecules and the large scale quantities we observe is as follows:

**TEMPERATURE**: Temperature corresponds to how fast the air molecules are moving; basically it measures how much energy each air molecule is carrying. When the temperature in Kelvin is doubled, the typical speed of an air molecule is increased by $\sqrt{2} = 1.41$, so the energy $mv^2/2$ is doubled. Hot air means air with faster moving molecules.

**DENSITY**: This is the mass of the air per unit volume, that is, how many molecules there are in each cubic centimeter of air, times the mass of a molecule. Air does weigh something, but because the molecules are so widely spaced from each other, it is very light compared to materials we are used to:

| (material) | g/cm$^3$ | ton/$m^3$ | pound/foot$^3$ |
|---|---|---|---|
| iron | 7.8 | 7.8 | 490 |
| rock | $\sim 2.5$ | $\sim 2.5$ | $\sim 160$ |
| water | 1 | 1 | 62.5 |
| wood | $\sim 0.6$ | $\sim 0.6$ | $\sim 37$ |
| air | 0.00120 | 0.00120 | 0.0750 |

**VELOCITY**: By this I mean, wind–the air moving, in the normal sense we experience it. Each molecule is moving at around 500 m/s, each in a different direction. If we average the speeds, we get some huge number like 450 m/s. But average the velocities–that is, speed *and direction*–and you typically find the air is at rest, or maybe moving at some slow speed. In other words, in air at rest, for each molecule going at 400 m/s to the right, there is one going at 400 m/s to the left. If the air is moving to the right, it means that slighly more of the molecules are moving to the right than to the left. For instance, if the air is moving at 10 m/s, it means that for each molecule going to the left at 390 m/s, there is one going to the right at 410 m/s. As the air molecules bounce off each other, each individually changes direction and speed, but the average stays the same.

Conversion: to get from m/s to mi/hr, multiply by 2.23.

To get from m/s to km/hr, multiply by 3.6.

**PRESSURE**: This is the most important concept of this lecture, so I will explain it slowly.

First, recall some physics concepts:

- Inertia: "resistance to moving," same as mass. Heavy things are harder to get moving than light things. Measured in kg.
- Velocity: how fast something is moving, distance/time. Measured in m/s. INCLUDES the direction the thing is moving in [it is a vector].
- Force: "what makes things move," measured in Newtons, N = kg $m/s^2$. One Newton gets one kilogram to move at 1m/s in 1 second (hence, seconds squared in the denominator).
- Acceleration: how fast velocity is changing, measured in (m/s)/s or m/s$^2$. You are accelerating when you speed up, when you slow down, *and* when you go around a curve (because your direction is changing).

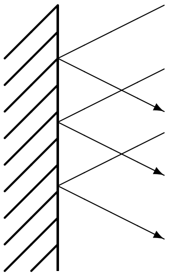
Two of Newton's laws will be very important to us through the course. The first is the force law,

$$F = ma$$

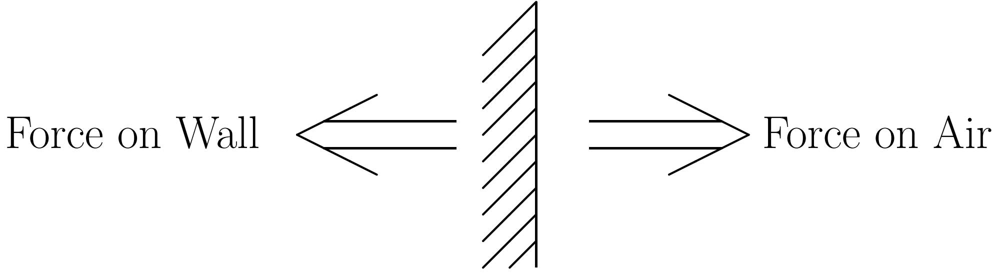
which tells how a force makes something accelerate: $F$ is the size of the force (say, in Newtons), $m$ is the mass (in kg), and $a$ is the acceleration (in $\text{m/s}^2$).

The second is Newton's third law, which basically says, if I push on you with force $F$, you must be pushing on me with force $-F$ (same size, opposite direction).

Now think about what happens when air meets a wall. The air molecules which are moving at the wall will bounce off:



(The shaded thing is the usual way to indicating a solid object.) Obviously the air molecules bouncing off the wall must have a force act on them, pointing out from the wall. They must then exert a force back on the wall, pushing it backwards:



The bigger the area of wall, the more molecules will bounce off it. Therefore the force is proportional to the area of wall (or whatever). When this is the case, it is convenient to define

pressure $P$

which is the force per area,

$$F = PA$$

with $P$ the pressure and $A$ the area. The MKS unit of pressure is the $\text{Newton/m}^2$, or $\text{kg/ms}^2$, called the Pascal. One Pascal is tiny: the pressure a piece of paper exerts on a table, because of its weight, is about 0.7 Pascal.

The more molecules in the air, the bigger the pressure, because there will be more molecules to bounce off the wall or solid object. Higher temperature also increases pressure, since the molecules are moving faster–and therefore hit harder and more often. Therefore pressure obeys

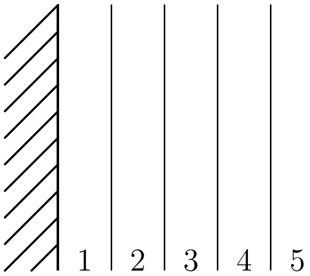
$$P = nRT$$

with $n$ the density of molecules (number/m$^3$) and $T$ the temperature, and $R$ some boring constant. Just remember that denser, or hotter, air has a higher pressure.

The pressure exerted by typical air is about 101,000 Pascal, or the force per area exerted by about 150,000 pages thick of paper. This enormous number comes about because, even though the air is very light, the molecules are moving with such enormous speed. (100,000 Pascal is called a “Bar.”)

The reason the air does not push us around is because it exerts force from both sides–our fronts are pushed backward, our backs are pushed forward, so we balance out. Our ribs don’t collapse because the air in our lungs pushes out with the same force as the air pushing in on the ribcage. The pressure inside our bodies pushing out, balances the pressure of the air. If the air were suddenly removed from one side of your body, the air on the other side would push you up to a remarkable speed very quickly, like someone in a space movie when they open the airlock. The air pushes down on the ground with the equivalent of about 10 tons/m$^2$ weight, or 14.7 pounds/square inch. The atmosphere is being pushed up by the same sized pressure. The reason it doesn’t fly off is that this is exactly the weight per unit area of the atmosphere. (Weight means mass times the acceleration of gravity $g = 9.8$ m/s. A kilogram of weight means 9.8 kgm/s$^2$ or 9.8 Newtons of force.)

The last comment in this lecture: why does air stand still? Because it is being pushed with the same force from all sides. Imagine cutting the air into thin slices and ask what happens to each slice:



Region 1 is getting pushed with pressure $P$, and force $PA$, by the wall. But it is getting pushed with force $-PA$ by region 2 The total force, which tells us whether the region will accelerate, is $PA - PA - 0$, so it stays at rest. Region 2 is getting pushed with force $PA$ by region 1, and force $-PA$ by region 3. Again, the forces balance and it stays at rest. Region 3 is getting pushed with force $PA$ by region 2, and force $-PA$ by region 4 . . . .