Temperature, Pressure and American Football - Introduction to Gay-Lussac's Gas Law

PROFESSOR JOHN LEONARD: Hi, my name is John Leonard. I'm a professor of mechanical engineering here at the Massachusetts Institute of Technology in Cambridge, Massachusetts. Today, we want to talk about the Deflategate controversy. Some of you may be familiar with this story. In the AFC championship game in January of 2015, there was an allegation that the New England Patriots cheated by removing some of the air from their footballs, which it's alleged would give them an advantage to be able to throw and catch the ball more easily and have a lower likelihood of fumbling. We're not going to decide the issue of Deflategate here today, but I want you to be the scientists to look at the underlying physical laws and the measurements, and try to get a sense yourself of what actually happened there -- so taking science to everyday life for the game of football to try to understand what may have happened in Deflategate.

Before we do that, we're going to ask you to do an activity first with the balloons. Your teacher will tell you what to do, but either using balloons or a plastic water bottle, I want you to see the effect on pressure by changing the temperature of a volume of gas.

Welcome back. So as you saw, when your balloon or your water bottle was placed in colder water, it shrank, and the reason this happens is that, as you know, air consists of molecules of gas that have energy, and as the temperature is lowered, the energy in the molecules is decreased. This causes the molecules to exert a lower force on the walls of the vessel containing the air, and so this shows in a way how the volume decreases due to decreased temperature.

When a balloon is inflated at room temperature, the molecules of air that are forced into the balloon begin to collide with the walls of the balloon, thus causing the walls to expand and the balloon to inflate. As long as the molecules have a high kinetic energy as they collide with the walls of the balloon, the pressure inside the balloon remains high, and the balloon remains inflated. When a plastic bottle with an uninflated balloon on the end is placed in warm water, the balloon starts to inflate.

Air is a gas and has molecules that are free to move around inside a closed container with a certain amount of energy. At higher temperatures, the molecules have higher kinetic energy, and therefore move with a greater velocity. A decrease in temperature, however, causes the air molecules to move more slowly with less energy. Since the molecules have lower energies, the collisions with the walls of the balloon are insufficient to keep the balloon as inflated as it was before. Therefore, the balloon deflates when the bottle is placed in cold water.

Now we're going to return to our role as scientists investigating the Deflategate controversy. In order to do so, we have to familiarize ourselves with the discovery of a French scientist, Joseph Gay-Lussac, who lived in the early 19th century. Interesting enough, Gay-Lussac conducted many of his important discoveries with the help of balloons, too. In 1804, Gay-Lussac made several daring ascents of over 7,000 meters above sea level in hydrogen filled balloons -- a feat not equaled for another 50 years.

These flights allowed him to investigate many aspects of gases. During those flights, he took pressure, temperature, and humidity measurements and samples of air, which he later analyzed chemically. Then in 1808, Gay-Lussac announced what would probably be his single greatest achievement, which subsequently became known as the Gay-Lussac gas law. The formula for Gay-Lussac's gas law is P1 divided by T1 is equal to P2 divided by T2, where P stands for pressure and T stands for temperature.

As you can see, a lot of what we're discussing involves pressure and temperature. And so what I'd like you to do is to talk amongst your fellow students to work on what is pressure, what is temperature? Can you come up with any sort of intuitive understanding and also hopefully a more formal definition-- what is pressure and what is temperature? And so I want you to work together just as there are moving molecules inside a football-- moving molecules of air, you might want to move around and talk to your fellow students and see what you can come up with for what is temperature, what is pressure? And we'll be back soon. I look forward to see what you found out.

Welcome back. So what did you decide for temperature? You have the molecules of air racing around inside the volume, and they sometimes collide with each other, which is rare, or much more often they collide with the walls of the container. These collisions are 100% elastic, meaning no energy is lost in the collisions.

To really understand temperature, we have to use the Kelvin scale, which is designed so that 0 Kelvin is defined as absolute zero. At absolute zero, a hypothetical temperature, all molecular movement stops. Temperature, when measured in Kelvin, is a number that is directly proportional to the average kinetic energy of the molecules in the gas. So when the gas molecules have a small average kinetic energy, the temperature is low. Large average kinetic energy means the temperature is high. See the animation on your screen now depicting low temperature and high temperature gases.

By the way, do you recall what is kinetic energy? Do you remember that kinetic energy is 1/2 mv squared, where m is the mass of the molecule and v is its velocity? You see that doubling velocity results in a factor of four increase in the temperature.

So now we've nailed down temperature as scientists, not just as folks that can read a thermometer. What about pressure? Was it something like this?

As the molecules collide with the walls of the container, there's a momentum change, and that causes a force. Pressure is defined as force per unit area. Pressure is simply a measure of how the molecules exert a force onto the container, and this force is greater when the molecules are moving around faster-- higher temperature-- and it's lower when they're moving around slower-- lower temperature. So now we've nailed down pressure, too. I bet you never thought there was so much science inside a football.

Let's get back to Gay-Lussac's gas law. P1 over T1 equals P2 over T2. When using this law, we have to be careful about measurement units. We need to use absolute pressure and temperature measurements.

The key thing is to use and understand the appropriate units for absolute pressure and temperature measurements. The pressure sensor that we will use measures relative pressure, also called gauge pressure. To obtain absolute pressure from relative pressure, we had atmospheric pressure to the measured gauge pressure. A typical value of atmospheric pressure is 14.7 pounds per square inch, or psi.

For temperature, we use Kelvin as our unit for temperature. Note it's simply Kelvin, not degrees Kelvin. Kelvin can be obtained from degrees Celsius by adding 273. So we can say Kelvin equals degrees C plus 273.

In our football discussion below, we will use degrees Fahrenheit. To get Kelvin from degrees Fahrenheit, we add 460 and then multiply by 5/9. So Kelvin equals degree Fahrenheit plus 460 quantity times 5 divided by 9.

Now, before we met today about two hours before we started filming, I took three identical NFL certified footballs and filled them each to the standard 12.5 pounds of air per square inch, psi. We did this in the laboratory here where the air temperature is a constant 74 degrees Fahrenheit. The first ball, ball A, I placed in a super deep freezer with a temperature of minus 13 degrees Fahrenheit. The second football, ball B, I just kept with me here in the lab. The third football, ball C, I placed into an oven with light heat at 102 degrees Fahrenheit.

Now here is your assignment. To see if you understand Gay-Lussac's law, I want you to use it to predict the pressures for the three footballs for the three different temperatures, and as a hint, I want to remind you to use absolute temperature measurements. Good luck. See you soon.

Welcome back. Did you do your calculations? Any difficulties? Now I have a surprise for you. Do you know what was the coldest game on record in the history of the NFL? It occurred on December 31, 1967 at Lambeau Field in Green Bay, Wisconsin. It was the NFL championship game. The Green Bay Packers played the Dallas Cowboys. What was the temperature at game time? You guessed it-- minus 13 degrees Fahrenheit. The game is still called the Ice Bowl.

Our ball A has been in an environment resembling the footballs of the Ice Bowl, and the psi number-- well, you can see that our measurement of 8.35 psi is well below 12.5 psi. Far, far away from the Ice Bowl in both time and distance on September 24, 1978 in San Diego, California, the very same Green Bay Packers played the San Diego Chargers and won 24 to 3. The temperature at game time was-- you guessed it-- 102 degrees Fahrenheit. Our ball C has been in an environment resembling the footballs of this a 100 plus degree game, and see again how the football's pressure is far from 12.5 psi.

So to review, we had three footballs-- A, B, and C-- that all started at an initial temperature of 74.1 degrees Fahrenheit, which you should have computed is 23.4 degrees in Celsius, or 296.6 Kelvin. The initial pressure was 12.5 psi, which is the relative pressure measured by our gauge, and so when we had 14.7 atmospheric pressure to that, we get 27.2 absolute pressure. So these values-- 296.6 Kelvin-- that's our T1, our initial absolute temperature-- and 27.2 psi is our P1, our initial absolute pressure.

For ball A, the temperature of minus 13 degrees Fahrenheit corresponds to 248.2 Kelvin. So to use Gay-Lussac's law to compute the predicted absolute pressure of ball A when we move it to the colder environment, we use P2 equals P1 times T2 divided by T1, which is 27.2 times 248.2 divided by 296.6, and that gives you 22.76 psi. We subtract off atmospheric pressure, the 14.7, and we get 8.06 psi, or 8.1 psi as our predicted pressure for ball A. For ball B, it stayed the same in the lab at about 74 degrees Fahrenheit, and so we should predict that the pressure should stay the same.

For ball C, our T2, our predicted temperature of 102 degrees Fahrenheit, is equal to 312 Kelvin. So applying Gay-Lussac's law again to compute the predicted absolute pressure of ball C-- again, P2 equals P1 times T2 divided by T1. That works out to be 27.2 times 312 divided by 296.6, which gives you 28.61 psi. We subtract 14.7 from that, and we get a predicted relative pressure for ball C of 13.91 psi.

Did you get the same or nearly the same values? I hope so. See the wide range of pressures all due to the wide range of air temperatures and the environments in which the balls were placed, and since we did an experiment here in the lab, we can compare these predictions against the observations that we got when we took our measurements as you saw in the video.

For ball A, which we put in the deep freezer, our measurement was 8.35 psi. We can compare this against our prediction of 8.06 psi. That's pretty good agreement. Ball B, of course, stayed close to 12.50 psi. We measured 12.55 pis. And for ball C, we got a measurement of 13.75 psi, which I think is also good agreement with our prediction of 13.91 psi.

Now that you know the science of Gay-Lussac's law and pressure and temperature, you're in a position now to be the scientist for you to make a prediction of what the pressure should have been for the footballs for the Patriots on the day of the AFC championship game, January 18, 2015. The game conditions for the 2015 AFC championship game were as follows. Several hours before the game, the Patriots footballs were measured in a 71 degree Fahrenheit locker room to have a pressure 12.50 psi. The balls were then taken onto the playing field where the temperature was 48 degrees Fahrenheit. For next activity, I want you to use Gay-Lussac's law to compute the predicted psi levels of the Patriots' footballs during the game, and again, remember to use absolute units.

Hopefully you used Gay-Lussac's law to compute an on field pressure of 11.32 psi. Now, during the game in the first half, a player from the Colts team intercepted one of the Patriots' footballs and felt that it didn't seem right. It didn't feel right. They thought it might have been underinflated. So one of the Colts staff made a measurement of the pressure on the field and measured that the ball was approximately 11 psi. The officials then did an impromptu measurement procedure in the beginning of the half time period in which they measured the eleven Patriots footballs.

They took the measurements with two different gauges. One happened to have a logo on it for the Wilson company that made the gauge, and one didn't, so well for refer to the two gauges as the logo gauge and the non logo gauge. The referee remembers using the logo gauge. The eleven measured values with the logo gauge are as follows-- 11.80, 11.20, 11.50, 11.00, 11.45, 11.95, 12.30, 11.55, 11.35, 10.90, and 11.35. In the next activity, I want you to take the average of these values.

What did you get for the average of the eleven measured values with the logo gauge? I got 11.49 psi for the average. So to summarize, our prediction from Gay-Lussac's Law was 11.32 psi, and the average of the eleven logo gauge measurements was 11.49 psi. So for the next activity, I want you to discuss amongst yourselves, based on this application of Gay-Lussac's Law and the measurements, do you think the Patriots' footballs were illegally deflated?

Now, as I said before, the referee had two gauges in his equipment bag that day-- the non-logo gauge and the logo gauge. And so what I want you to do now is to repeat the work you did earlier for the measurements from the non-logo gauge, and the values from that-- I've written them down here-- are 11.50, 10.85, 11.15, 10.70, 11.10, 11.60, 11.85, 11.10, 10.95, 10.50, and 10.90.

So what I want you to do is repeat the work you did before computing the average for those eleven measurements, and compare that against your prediction that you made before from Gay-Lussac's law, and discuss amongst yourselves. If the referee had used the non-logo gauge to check the balls before the game, do you think that there was tampering with the footballs?

In performing scientific experiments, it's extremely important to think about the sources of error in your measurements. In the Deflategate procedure, some of the unknowns in the measurement process were that the times at which the measurements were taken were not recorded, the temperatures of, say, the locker room where the measurements were taken were not written down, and there were other sources of error, including some of the footballs were wet because it was raining that day. That would cause the leather to swell and the volume to increase, which causes the pressure to drop.

So what I'd like you to do now is to discuss amongst yourselves what are some of the sources of error in the Deflategate measurement procedure, and how would these impact your conclusion if you go back to our scientific sort of processes to take predictions from a physical law—Gay-Lussac's law-- and compare them against measurements? When you account for the sources of error that I mentioned and other sources of error that you can come up with yourselves, how does that affect your conclusion on whether there was tampering or not?

To finish up our discussion of Gay-Lussac's law, I want to ask you to do one more calculation and to discuss the result. Gay-Lussac's law is actually a special case of the ideal gas law-- PV equals nRT. Perhaps you've seen this in one of your classes already, or maybe you'll see it later in your science class this year. PV equals nRT expresses the pressure, P, times the volume, V, has to be equal to the number of moles of gas, n, times the universal gas constant, R, times the temperature, T. And we need to use absolute temperature and absolute pressure for the ideal gas law to hold.

So what I'd like you to do now is to think about, OK, what if there was tampering? So suppose earlier you computed a difference between the predicted on field pressure for the 48 degree Fahrenheit temperature on the field versus the measurements-- the average of the eleven values between the two gauges, and you also discussed the error in the measurements, but what if you assumed that some of the air was removed from the football? So there was tampering. Suppose there was tampering, which means the number of moles of gas, n, would be reduced.

What I want you to do is to calculate, what is the difference in the number of moles of gas? What's the percentage difference in air? What percent of air needed to be removed to get the difference in pressure that you observed? So what I'd like you to do now is to use the ideal gas law, PV equals nRT-- and be careful to use absolute units-- to compute the change in the amount of air in the football that you need to see the difference between the predicted and measured pressure values.

Using the ideal gas law, we can compute the reduction in n, the number of moles of gas, that achieves the difference in pressure between the Gay-Lussac's law prediction and the measurements for the non-logo gauge. And this difference of 0.21 psi-- that's the difference between 11.32, our prediction, and 11.11, the average of the non-logo measurements-- works out to be-- if we want to figure out the percentage of air that would have been removed from the footballs to achieve that production, it's 0.21 divided by 27.2, the absolute pressure, which is 0.77%. So less than 1% of the air would need to be removed from football to achieve the difference in pressure.

Thanks everyone for participating in this BLOSSOMS activity. I hope it's been a good illustration of how the laws of physics apply in an important everyday real life situation. At MIT, I do research in robotics, self-driving cars, and autonomous underwater vehicles, and my work involves predictions from physical laws, measurements, dealing with uncertainty, and making decisions. And so in a way, Deflategate is a nice microcosm of some of the problems that scientists and engineers face in doing advanced research, and I think that there are great lessons here that you can take forward in your career as a student and hopefully as a scientist or engineer one day.

Hi. So I really want to thank you for looking at this BLOSSOMS lesson. For myself, I'm a big American football fan. I actually support a different team, the Philadelphia Eagles, so I don't really like the Patriots, but I was drawn to this because I teach measurement and instrumentation at MIT to the juniors in our mechanical engineering major, and this class looks at measurement and instrumentation. A big part of it is dealing with measurement units and making predictions from physical laws, comparing them against observations, and then trying to give the students a feeling for how you account for measurement error and uncertainty in processing and interpreting data.

And in our class, we're always looking for real world examples. How do we bring science into the everyday life of the students? And so I was drawn to Deflategate. I became deeply obsessed with it, I have to confess, because I really felt it would make me a better teacher. I felt that it would provide a good real world example to explain not only some basic physical laws like Gay-Lussac's law and the ideal gas law, but also how you deal with measurement error and how you think about uncertainty in a measurement problem.

So I kind of feel like the legacy of Deflategate-- to me, it would be fantastic if, from what was honestly sort of a debacle of the last year and a half for the sports media in this country, that, if as some outcome of that, we might have a real world example that could give students-- say, high school students-- a good example for them to understand Gay-Lussac's law and to have a sort of confidence to dealing with absolute measurements of temperature and pressure and to use that for something in real everyday life.

So the key learning objectives for this BLOSSOMS activity are, number one, to understand Gay-Lussac's law and to apply it to everyday life, and number two, to think about the process of measurement and dealing with uncertainty in comparing predictions from a physical law with multiple measurements of a physical phenomenon that have uncertainty. So the activities in the lesson are designed to hit these objectives by starting with sort of from pre-req perspective I'll assume that the students can do basic arithmetic and maybe some-- they don't even need algebra. It's amazing actually how to use Gay-Lussac's law it's really just multiplication, division, addition, subtraction. And probably from a learning objective perspective, dealing with the absolute units-- so using Kelvin instead of degrees Fahrenheit or degrees Celsius-- that's probably one sort of leap that students may not have seen before, and also dealing with absolute pressure measurements where you need to add atmospheric pressure to gauge pressure measurements. That's another sort of thing that students need, but if they use the right units and basically using absolute pressure and temperature use units, I feel like Gay-Lussac's law is really accessible to high school students or even middle school students, and so my hope is that the activities in the lesson will be accessible to the students and will give them confidence to sort of think on their own about this problem.

So what I'd like to do now is talk through some of the activities in just a little bit more detail, and so activity one we chose to use a balloon, or you could use a plastic soda bottle, and simply placing the balloon in cold water to see the effect of the change in volume that comes from the decrease in temperature. With the footballs in the Deflategate analysis we assume that the volume is constant sort of to first order. Now, in reality, if the football gets wet, the volume can increase, and studies have shown that that might have been a factor for-- so if the volume increases, the pressure will decrease. And really if you're in-- the specification for Deflategate is that the pressure of the footballs should be between 12.5 and 13.5 psi measured before the start of the game, but that specification is, in my view, thermodynamically flawed because just knowing the pressure without knowing either the temperature or the volume doesn't really tell you something.

And so the exercise with the balloons relates more to the effect in change in volume due to the decrease in temperature of, say, putting the balloon in cold water, but hopefully your students will enjoy doing that, and it will give them some intuition for the gas law. And with a balloon you can see the effects so readily. We thought that was a nice thing to add here.

For activity number two, we're asking your students to discuss what do temperature and pressure really mean, and they should do this with each other, and hopefully it'll lead to some animated discussions. And if you're looking for intuition about, say, what pressure is-- and I'm sure many of you know this-- you could use the analogy between, for example, a skier on skis versus a skater on ice skates and say which has a greater pressure. And so if pressure is force per unit area, for a person on skis, the force is spread over a much greater area, and so the pressure is lower. For a person on ice skates, the actual area of contact with the ice surface from the blades of the skates is very small, and so the pressure is very high.

And so hopefully students can articulate both sort of a qualitative understanding of pressure and also a more sort of formal or quantitative definition with force per unit area, so Newtons per meter squared. For temperature, hopefully students will be able to articulate how the molecules of a gas are continually in motion and that the temperature is really a measure of the energy of the molecules, which are sort of zipping around inside this sort of container like the football or the balloon. And hopefully they can draw from their everyday experience. Perhaps in their everyday life, they're in a country that uses Celsius or a country that uses Fahrenheit, but hopefully they will also have some notion of using Kelvin and absolute temperature measurements.

So in the third activity, we want students to actually use the Gay-Lussac's law to make the predicted pressure computations for the three footballs, and so if we have the football at 12.5 psi to start-- and so we had 12.5 psi going into the cold minus 13 degree cooler-- the pressure is going to drop, and it's going to drop to about 8 psi. And so hopefully your students will get some intuition for that, and maybe if you have the facilities-- for example, if you did it safely with some dry ice in a cooler, you might be actually able to reproduce in your classroom a minus 13 degree cooler like we did in the video and show how the temperature dropped to minus 13 degrees Fahrenheit-- gives this corresponding drop in pressure of about 4.5 psi depending on your starting temperature. And then likewise for the ball C that went into the oven, you saw in the video that the pressure increased from 12.5 up to about 13.75 psi, and that simply just comes from the increase in temperature causes increased energy of the air molecules, which relates to a greater force per unit area on the interior of the football.

One thing you might want to do is, if you have access to gauges, you can actually make the measurements that I made, and you can have the students sort of try themselves, for example, and it doesn't have to be to minus 13 degrees. You could stick a football in a fridge. Now you do have to wait, obviously, for the temperature to equilibrate, but sometimes as much as even 20 minutes wait, 30 minutes wait you can see the effect. And so I've done lots of experiments myself sticking footballs in the fridge. My wife laughs at me for some of the experiments I've done. I've had footballs in a big bag of other sports balls out in my car with the windows and the doors open to do an experiment of being in the cold and bringing into the warm. So hopefully the students can do the Gay-Lussac's law calculation and get the right prediction.

So in activity four, we moved to the actual setting of the 2015 AFC championship game, and here the field temperature was 48 degrees, and the locker room temperature was 71 degrees. And so in this activity, the students predict what the on field pressure should have been, getting an answer of about 11.32 psi if you assume starting in a 71 degree locker room to a 48 degree field. So hopefully students will be able to make that prediction.

And then in activity five, we gave the eleven measured values with the logo gauge. And this is a great example of comparing measurements which have some scatter. So you might, for example, have the students graph the eleven measured values and see the sort of variation. Some of that might come from the fact that the ball is being wet might cause-- in particular, in the game, one or two footballs were used right before the half for an extended drive by the Patriots in which the balls got pretty wet, and you can see that from the game video. And so in that instance, the wet leather would expand and cause the pressure to drop. So students should take the eleven pressure values and get the average in activity five.

And then in activity six, we compare the prediction and the observation, and what the student should see is the actual observations are higher than the on field predictions, so 11.49 versus 11.32 psi. Now, when the balls were taken into the locker room at halftime, they did start to warm up. Now, they were kept in a bag, and they were probably taken out one by one is our best guess from the various reports on what happened. And so the balls would be warming over time, and so at a more advanced level, I would actually plot the pressure and temperature over time for warming and cooling.

So there's something called-- perhaps you're familiar with Newton's law of heating or cooling. This would be a great, more advanced activity. You can plot the exponential increase in the temperature value, and I that would be a great activity for more advanced students, but there was enough time for a little bit of warming in the half time interval, and to my opinion-- not that I want to sort of-- I want students to reach their own conclusions, but my feeling is that for the logo gauge the measurements have a really good match to the predictions.

So that's activity six, and we ask students to think. Do they think there was tampering? How did the predictions match the measurements?

Now, in activity seven, we use the other measurements, the measurements from the non-logo gauge. Now, this was a source of some controversy if you followed this Deflategate matter closely. The league's consultants found that the referee must have used a non-logo gauge. I don't want to get too much into it here, but if he used a non-logo gauge, you will see a bigger increment-- a bigger potential increment, a bigger difference between the prediction and the observation. And for that, you kind of need to make a judgement call about is this a good match or a bad match relative to all the different sources of error and uncertainty, but I think it's a really interesting problem, actually. There's a lot in here. There's a lot in here.

I've been looking at this for about a year and a half, and every time I go back to it every few months for a lecture, or a talk at a seminar, or something, I find new things about this problem. It really has a lot I think that could teach us about this.

So in activity eight, we asked the students to think about error, and I mentioned a few in the video, but in general, dealing with measurement error-- dealing with uncertainty is the art of measurement. And really, if you have a good prediction from a physical law, it will help you know if your measurements maybe are sort of working or not working. It's pretty easy, actually, to try to do a measurement process and wind up realizing that you didn't record the right things or your procedure was messed up.

In our measurement and instrumentation class here-- something called 2.671 here in the MIT MechE curriculum-- each student does their own individual measurement project called Go Forth and Measure in which they pick an everyday life phenomenon that involves measurement. It might be something from athletics, or cooking, or bicycling, and all sorts of things. And this is a wonderful experience for our students where they take measurements, make predictions from physical laws, and analyze their data. And what invariably happens is that, A, the first time they do an experiment they kind of mess it up, but they learn a lot from that. And B, dealing with the uncertainty in the measurements and understanding error is usually one of the greatest challenges.

One of the sad things about Deflategate-- it only happened once. It was the first time they got to make these measurements, and in hindsight, if they could do it again, it would be great to record the measurement times. It would be great to do a lot of other things more systematically, but with the information we have, I still think this is a great case study in the science of measurement.

So hopefully the students in activity eight will discuss some notions of error amongst themselves. For example, the gauges have some drift over time, and they're actually inexpensive sensors for tire pressure measurements. So if your car has something that says low tire pressure like an alert that you might have a flat, those don't really need to be that accurate. And so my opinion is that those pressure sensors are only accurate to a few percent at best. And so the quantities that we're looking at here are order of 1% of the removal of the air-- removal of 1% of the air or the football, which gets into activity nine, actually, which I admit this one might be more advanced for some students, but in activity nine, you kind of work backwards and say, OK, well what if there was tampering?

If we use PV equals nRT, we can calculate the change in n, the number of moles of gas that you need to have to get the corresponding change in pressure. And so for a 0.3 psi difference, if you take 0.3 divided by the sum of 14.7 plus 12.2, or 0.3 divided by 27.2, then you can calculate, well, what would actually be-- how does that correspond to the difference in the amount of air, the number of moles of gas? And so if you assume the temperature is constant, the volume is constant, then you can calculate-- and I'll just do it here just to be a little careful here-- but 0.3 divided by 27.2. And you get 0.011, or about 1%.

So my personal opinion is that it's hard for me to fathom an illegal tampering scheme to remove 1% of the footballs' air when you can see from the oven experiment and the cooler experiment you get much bigger variations in pressure simply just due to mother nature, but in this last activity, we asked the students to go beyond Gay-Lussac's law to the ideal gas law, and that will give you opportunities to talk about the actual moles of gas, things like Avogadro's number. It's actually a nice way to broaden the discussion a bit if you feel your students have had the background for that.

So in summary, I just really want to thank you for considering this BLOSSOMS lesson. I think it has a lot to give us, and I hope that it's fun for your students. Thank you.