DO GECKOS STICK BECAUSE OF CAPILLARY ACTION?

DAY 6

LESSON OVERVIEW

Lesson Description

The next two lessons consider the hypothetical mechanism of capillary action. Until recently, scientists debated whether geckos had a very tiny layer of water on their feet that allowed them to adhere to surface through dipole-induced dipole interactions. Students in today's lesson will bend three types of liquid (polar, nonpolar, and amphoteric) and ascertain that water behaves abnormally compared to the less polar liquids. The teacher then reviews electronegativity and shows students how to determine bond moment.

Learning Goals

1. Students will distinguish polar and nonpolar covalent bonds by evaluating the distribution of electrons between a pair of bonded or interacting atoms.
2. Students will use the relative electronegativities of bonded atoms to determine the polarity of the bond.

LESSON PREPARATION

Teacher Background Content Knowledge

When a narrow glass tube is placed in a liquid, the liquid may either be pulled up in the tube or pushed down, depending on the forces between glass molecules and liquid molecules and between the liquid molecules themselves e.g. water will rise in the tube, while mercury will be depressed. This phenomenon is called capillary action. An example of capillary action from every day life is sucking up water by dipping a towel or a piece of paper into the water.

Many insects and frogs make use of capillary forces to adhere to surfaces. The gecko, however, lacks glandular tissues on its toes and hence cannot produce the liquid needed for the capillarity. So at first it may seem strange to suggest this type of intermolecular force as the explanation to the stickiness of the gecko, but even in very dry air there is still enough humidity to leave some layers of water on surfaces, which could facilitate capillary action.

In order to find out whether capillary forces are involved in gecko adhesion, Autumn *et al* (2002) carried out an experiment based on the following argument. In order for the capillary force model to work, the setae (with their hypothetical layer of water attached) must be very hydrophilic, so if a foot or a seta was placed on a hydrophilic surface it should adhere strongly, whereas it would stick poorly to a hydrophobic surface. Measurements were done for both a whole foot of live animals and for a single seta.

In the foot measurements a toe was placed on either a hydrophilic (SiO_2) or hydrophobic (GaAs) semiconductor wafer (diameter 50 mm). A force-gauge was attached to the wafer, recording real-time force data. The gecko was pulled down until it detached from the wafer. While pulled down the gecko was restrained by hand, and the other toes were held in a fixed position. This procedure was repeated for 9 geckos. In order to be able to compare data from the 9 animals, the ratio of maximal force and toe area was calculated.

In the experiment with a single seta, setae were carefully removed and individually placed on two different surfaces: one polar and one non-polar MEMS[1] cantilevers. The seta was connected to a micro force gauge (analogous to a spring scale). Then the amount of force required to remove the seta was determined. The resolution of the measurements was ±0.4 μN.

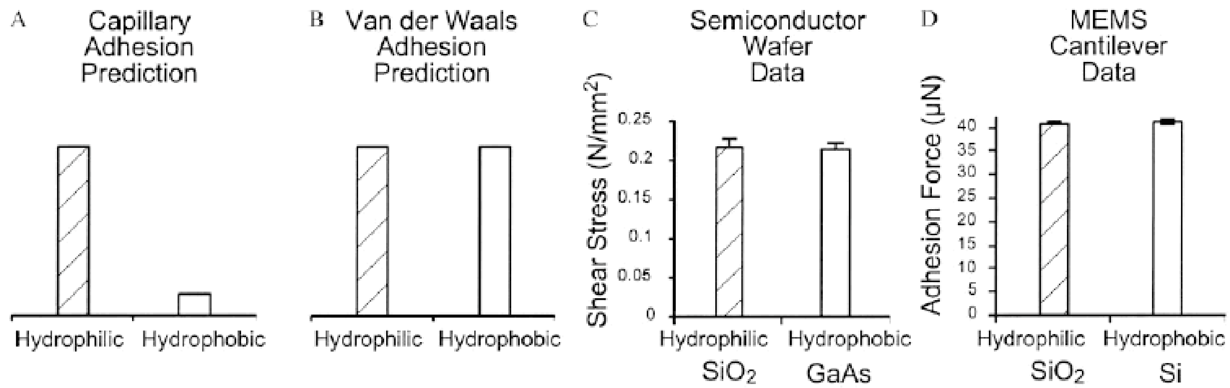

Fig. 1. Force of gecko setae on highly polarizable surfaces versus for surface hydrophobicity. (*A*) Wet adhesion prediction. (*B*) van der Waals prediction. (*C*) Results from toe on highly polarizable semiconductor wafer surfaces differing in hydrophobicity. (*D*) Results from single seta attaching to highly polarizable MEMS cantilevers differing in hydrophobicity. Note that geckos fail to adhere to hydrophobic, weakly polarizable surfaces [polytetrafluoroethylene where θ = 105° (25) and the dielectric constant, ε = 2.0 (23)]. Adhesion to hydrophilic and hydrophobic polarizable surfaces was similar. Therefore, we reject the hypothesis that wet, capillary interactions are necessary for gecko adhesion in favor of the van der Waals hypothesis.

Figure 19. Figure 1 from Autumn *et al*. (2002) showing how the van der Waals force (London dispersion force) explains the stickiness of the gecko setae.

The data of the experiments together are shown in Fig. 1c, d. Also shown in Fig.1 is the predicted outcome of the experiment based on either a capillary force or a van der Walls force model for the stickiness of the gecko. The data clearly shows that capillary forces cannot be the main factor in the adhesion of the gecko.

Student Prior Knowledge Expectations

This lesson assumes that students have already learned about covalent bonds and Lewis structures and have some sense of molecular geometry (if knowing nothing more than that some molecules extend beyond one plane of geometry).

Potential Student Alternative Ideas

[1] MEMS stands for MicroElectroMechanical System. The MEMS used in these experiments are based on Atomic Force Microscopes (AMF).

Many students fail to consider that electrons in covalent bonds may not be shared equally. When they are aware of bond polarity, they often simply assume that the atom with the larger number of valence electrons will receive electron density (Peterson 1986). Many students do not consider electronegativity when determining bond polarity. They may also confuse ionic and covalent bonds (Taber 1995)and assume that the atom with the larger negative ionic charge will receive more electron density in the bond (Birk 1999). Finally, a few students consider the size of the atom and even the non-bonding electrons when thinking about bond polarity (Birk 1999).

Potential Student Difficulties

We have removed many of the accessory skills needed to analyze bonds in order to allow students to focus on the role of electronegativity in determining bond polarity. So rather than having students start from scratch and determine the Lewis structure from the formula and the periodic table, we provide students with the structure. Coordinating all of these different skills may be too difficult. However, if students are capable of starting from the formula, then by all means adapt the problems. If the length of the unit was longer, then we would definitely do so.

Materials

Item	Number/Amount
Burettes, separatory funnel, or syringe	1 per group of 3 students
Burette clamp	1 per group of 3 students
Stand	1 per group of 3 students
Tap water	Enough for 3 stands (roughly 150 ml)
Ethanol	Enough for 3 stands (roughly 150 ml)
Hexane or vegetable oil	Enough for 3 stands (roughly 150 ml)
Catchment trays	1 per group of 3 students
Beakers (100 ml)	1 per group of 3 students
Funnel	1 per group of 3 students
balloons	1 per group of 3 students
Comb or plastic straw	1 per group of 3 students
Square of fur or wool	1 per group of 3 students
Square of polyester	1 per group of 3 students
protractors	1 per group of 3 students
White index card	1 per group of 3 students
Tape	1
Tennis ball or hacky sack	1

Cautions/ Potential Pitfalls

Students will be bending liquids using a balloon or comb. The liquids will have to be collected using a tray of some sort. Make sure the trays are large enough to catch water as it deflects to a large angle! If you don't have burettes, you may be able to rig a substitute using a syringe. Draw up the syringe with the liquid to be tested and then clamp the body of the syringe to a stand. Remove the plunger and the liquid should drain from the syringe or procure an adaptor that allows you to attach a stopcock (often called a Poor Man's Burette). However, you will need a syringe with a volume of at least 50ml for this. Finally, before doing the lab, determine what distance away from a stream of water, you can hold a balloon and NOT have it curl, so much that it touches the balloon. Once the rod is wet, then the fur gets wet, and you will have trouble conducting the lab in later classes! Tell students to hold their charged rod at a safe distance. (We have found that 2 inches usually works well, but this varies with the humidity.)

Pre-Class Preparation

Getting the Materials Ready

Before class clamp the burettes to their stands. Also pore the liquid to be tested into a beaker at each lab group work area. Most burettes can only hold 50ml, so this should be adequate. This lab has students rotate, so if you have 9 stations that translates into 3 stations with water, 3 with ethanol, and 3 with a non-polar liquid like hexane.

Safety Issues

If you use hexane, you might want to reserve this as a demo, and just have the kids do water and ethanol for themselves. Hexane is highly volatile and without good ventilation, you might have students who get headaches.

DOING THE LESSON

Opening

Teacher and students review HW. Teacher reviews the process of testing hypotheses and falsifying them. She discusses some of the hypothetical explanations that have been investigated so far and notes how research results from gecko experiments so far have disconfirmed these explanations. Teacher may also choose to address any feelings of frustration. Students may complain that they keep finding that their explanations were wrong. In fact, depending on the class, after day 6, most of the hypothesized explanations generated at the beginning of unit may have been falsified at this point. Reassure students that the answers don’t come quickly or easily. This is the way science actually works. Teacher may want to share the following quote with their students: *Results! Why, man, I have gotten a lot of results. I know several thousand things that won't work.* —Thomas Edison Teacher might remind students about the possible benefits of	

understanding gecko adhesion. New technologies take time, but they offer exciting rewards once they have developed. Teacher then tells students that they are going to investigate some possible explanations that no one in the class has generated. These explanations are probably new or unfamiliar to most of the class. This represents a new phase of the unit. Before students were reviewing their initial ideas, but now they will be learning new chemistry content.	

Demonstration

Teacher takes a dry piece of paper and holds it against the wall. She then releases her hold and comments on the paper falls. She might say: "Normally, paper doesn't stick to a wall. However, one can make it do so with glue, but we have already ruled that out as a possibility." Teacher asks if there is another way to get the paper to stick and then takes responses. If responses are just variations, teacher asks students to compare their suggestion with one of the previously tested explanations for gecko adhesion. If wetting is not mentioned, teacher suggests wetting. The teacher wets the sheet of paper by placing it in a tray of water. Teacher picks up the paper and allows the excess water to drip off. She then presses the wet paper to the wall and releases hold. She might say to them: "There is actually something 'sticky' about water. Think about when people try to balance a spoon on their nose. What they do if they are having trouble? They breathe on the spoon to moisten it. Another example is trying to pick up a sheet of plastic wrap off of a wet table. It's difficult. "Perhaps the gecko might has a thin layer of water—and I mean very thin, perhaps a few molecules thick—which would allow it to stick to surfaces. Water is abundant, and the vapor in the air is a ready source of water as it can adhere to surfaces. "Today and tomorrow we are going to explore how and why water is 'sticky' and see if perhaps geckos use in some way to stick to	Teacher states purpose of lesson.

walls.	

Activity 1 – Bending Streams of Liquid

Rationale: The students learned about induction the previous day. Students may believe that the bending of a stream of water by a charged object is another example of induction. Only by showing that other substances (nonpolar and amphoteric) do not behave the same as water can we make the case that something more than induction is at work with water. If ethanol bends well, but hexane doesn't, we can give students the chemical formulas or Lewis structures and ask them to think about what might be responsible. This focuses on the OH bond and allows for a review of polarity again.	See student materials entitled "Bending of Liquid Labs"
This lab has three rotating stations that differ only by the substance being tested. Each station has a burette filled with one of three liquids: hexane, ethanol, or water; a piece of wool or fur and a balloon. Students will also find a protractor with a white note card affixed to the back, a burette stand, and a pan to be placed under the burette to collect the liquid.	Students test with both a comb and a glass rod to demonstrate that is attracted to both positive and negative charges.
Students will charge balloon with the fur. They will then open fully the stopcock on the burette and place the balloon within 2 inches of the stream of liquid. If the stream bends, they will record the angle from 90° to which the stream bends. They will then take their piece of fur and try to bend the stream of liquid.	Have students standardize the charging, perhaps by agreeing to rub the balloon the same number of times with the fur.
THE TEACHER SHOULD DEMONSTRATE THIS FOR THE CLASS PRIOR TO HAVING THEM GO TO THE STATIONS.	
Students will stop the burette and recharge the balloon. Then they will repeat this from the other side of the stream and record the angle. They will close the burette again.	
This process once kids have gotten the flow should take seven minutes total.	
Now have the students rotate the next station, which has a different liquid to be tested.	If students are taking longer, then have them do two out of the three. The data will be shared anyway, so they will still be able to see data for all three liquids.
As students complete a station, have one group member go to the board to report data. Once the lab is over, have the groups calculate the different averages for the three liquids and report	Keep the data on the board for consultation tomorrow.

back to the class.

Students are asked to answer the following questions after completing the lab stations:

1. Looking at your data, how do the different liquids react to the charged object. Use data to support your claim.

[Water has the greatest angle.

2. How would you explain your observations?

[Hopefully, students will cite induction. If students ask, tell them that the liquid is neutral.

3. What effect on angle of deflection does the side on which you bring the charged object have?

[No effect]

4. After rubbing, the fur is positively charged whereas the balloon in negatively charged. Does the sign of charge on an object matter?

[No effect—the trend should still hold.]

5. Does induction have a role in your observations? Explain.

[The charged object causes electrons to move away from or towards the object based on its charge. This creates an imbalance in charge in the stream of liquid, which then is attracted to the charged object.

6. Does induction explain all of your observations? Explain.

[The liquids didn't behave the same. Something else must be going on.

Alternatives to this lab:

The teacher could have students bend a stream of water from the taps at each lab bench using the balloon and record the angle of bending.

The teacher can follow up this mini-lab with a demonstration of the other two liquids. This will save time and set-up for the lab (one only needs to put together two burettes rather than 6 or 9 for the lab above).

Students could be asked to predict what will happen to the ethanol

This is a great way to save time, but still allows students to experience the phenomenon with water directly.

and the hexane. The teacher would still use a protractor to measure the angle and have the students think about why the effect is less.	

Teacher Talk

What follows is an example review of electronegativity and the bond moment. "Chemists and physicists try to use the structure of matter to explain the behavior of that material. Let's look at the Lewis structures for the three liquids we tested. [Teacher draws pictures like those below: "Based on our data, we found that water bends by ….. degrees, ethanol by … degrees, and hexane by… degrees. "Now based on our **work from yesterday on induction, we know that a charged object can induce a charge in a neutral object and cause it to be attracted to it**. That's how the paper pieces were drawn to the straw and stirring rod yesterday. Ask you students if they think induction is responsible for the bending, then ask whether they would expect the effects to be equal for all liquids or not and why. They can then think about what it could be about each liquid that causes the difference in bending. After discussion **the teacher asks students to consider what about the structures might be responsible** for the different bending results. **Possible Reponses and Further Prompts:** ***-If students say having hydrogens affects the bending,*** ask them why. Note that all the molecules have hydrogen, and then ask how this would explain a difference. Remind them that differences explain differences, that is, a difference in the structure is often the source for a difference in behavior, in this case, the bending angle of the liquid stream. ***-If students say that not having a carbon,*** then affirm the student's idea. Though this is not the right answer, they would be right to note that there is a correlation, from the	

examples chosen for this lab, between fewer carbons and greater bending angle. Make sure to open up the discussion by asking whether this is the only element to change in number between the structures. This allows the teacher to apply the student's principle to another group, such as the hydroxyl, -OH, which is ultimately responsible.

-***If students say O-H***, then ask them why. Students should note that the two chemicals that bend the most have an O-H, whereas the one that doesn't bends the least. Ask them how many O-H bonds are in each molecule; have them note that water actually has TWO O-H bonds, [underline them] and so the trend is even stronger. More O-H bonds, then the greater the angle of deflection.

"Let's look at the O-H bond. [Pass out electronegativity sheet]

[Grab a ball or hacky sack to represent an electron and toss this between oneself and a stuent]

"Remember from earlier that these are covalent bonds and that this involves the sharing of electrons back and forth between the two atoms. But remember from before that just because two atoms share electrons that doesn't mean they share them equally.

"But first how would you know if two atoms were sharing an electron equally?

"So if the electron spends on average equal amounts of time on each atom, then that is equal sharing. What about unequal sharing?

[Teacher repeats the demonstration above, but holds onto the ball longer than the student.]

"So, unequal sharing is when the electrons (remember there are two in a bond) reside on one of the two atoms more than the other. In chemistry, we say that bond with unequal sharing is polar OR has a bond moment. Either one will work: polar bond or bond moment.

Ask students to consider if this unequal sharing affects the charge of the bonded atoms.

"Let's take a look at the electronegativity sheet that I just passed out. Electronegativity is a measure of how much an atom holds onto an electron. So the higher the value, the more likely an atom will retain or 'hog' an electron. There are many ways to calculate electronegativity, but it is a bit beyond this level of chemistry to explain these methods. For now, we'll take it on faith that electronegativity measures what I said it did.

"Does anyone remember how we determine whether bond has equal or unequal sharing? Right, we find the two values for each atom in the bond and we subtract the two. The difference, if great enough, tells us how equally the two atoms are sharing the electrons in their bond.

Here is a table that you will remember from earlier:

Type of covalent bond	Difference in Electronegativity
Non-polar	$D \leq 0.4$
Polar	$0.4 \leq D \leq 1.0$
Very polar	$1.0 < D < 2.0$

[Teacher then does calculation for O-H and shows that it has a very polar bond, meaning that the electrons in the bond are unequally shared.

"We know that they are shared unequally, but we are also interested in which atom has the electron density for a longer time on average. Remember that the atom with the higher electronegativity value is the one that 'hogs' the electrons.

"Will that change the charge on that atom? In what way? Why? - if there are no responses, ask students to remember that electrons are negatively charged. If they reside on one side of the bond, then what do they do to that side? [They make that side more negative, whereas the other side of the bond becomes positive, since it now has more protons on average than electrons.] One could draw a picture like the following below:

[Insert picture]

"Recall that we often symbolize this unequal sharing with bond moment symbol: +→. The head of the arrow points to where the electrons reside more often, and the positive end is beside the atom that loses the electron density.

See appendix 2 for the electronegativity chart and the table below.

Teacher may want to write the definition for electronegativity on the board.

[Stress that thewater molecule is over neutral—electrons have not been lost.

"Let's look at the C-H bond in hexane. If we subtract the electrogenativities (2.5-2.1) we find the difference is too small. So these atoms share their electrons nearly equally. So this bond would be nonpolar. Because the electrons are shared equally, the numbers of protons and electrons on both atoms are balanced, so there are no areas of charge.

"How might this explain the behavior of hexane compared to water when we bought the balloon towards them?

[Stress that the picture is more complicated and that we have to consider all of the bonds in a molecule not just one, but that this notion of polar bonds will important in determining the bending patterns seen. Tomorrow we will take up the rest of the story.]

"Let's practice. Determine what type of bond (nonpolar, polar, very polar) exists in the two molecules and draw in the bond moment symbol. The two chemicals are HF and SO_2.

[Teacher draws the Lewis structure for the students.]

	Electroneg		Electroneg.	
H	2.1		S	2.5
F	4.0		O	3.5
difference	1.9		difference	1.0

HF has a very polar bond, whereas SO_2has two polar bonds.

[Teacher wanders through class helping students. Depending on time teacher either covers the problems or asks students to come to the board to present.

SO_2 has two bonds; one is a double bond and one is single (we'll neglect resonance unless you have already covered this). The type of bond, double or single, doesn't affect how bond moments are calculated using an electronegativity chart.

Homework

Homework tonight isn't about the geckos. In order to understand how water is sticky and therefore, how geckos might use water or water's strategy to stick, we need to review bond moments. We will return to the gecko, but we will take a small detour first. The homework involves determining the type of covalent bond and drawing in the bond moments for the following molecules: HCl, CO_2, NH_3, CH_4. Depending on how well your students can create Lewis structures from formulas, you may wish to include the structures as well.

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DO GECKOS STICK BECAUSE OF CAPILLARY ACTION?

Day 7

LESSON OVERVIEW

Lesson Description

Students will use their understanding of bond polarity to predict molecular polarity. They will construct molecules made of marshmallows and sum the bond moments in order to determine whether the molecule would line up in an electrical field.

Learning Goals

3. Students will determine whether a bond is polar or not based upon the electronegativities of the bonded atoms.
4. Students will determine the overall polarity of a molecule based on the individual bond moments in the molecule and the geometry of the bonds to see if the moments are additive or not.

LESSON PREPARATION

Teacher Background Content Knowledge

See Day 6.

Student Prior Knowledge Expectations

See Day 6.

Potential Student Alternative Ideas

In addition to the alternative ideas surrounding bond moments, students may also harbor additional misconceptions about dipole moments or molecule polarity. Some students may assume that if a molecule has polar bonds, then it must also be polar overall (Birk 1999). Other researchers have documented instances when students fail to relate electronegativity to dipole moment and even go so far as to consider a polar covalent bond as a different type of bond than covalent bonds, a separate class like ionic bonds (Nicoll 2001). Unsurprisingly, some students also consider polar molecules to have fully charged ions incorporated into their structures (Coll 2001).

Potential Student Difficulties

Geometry. Students who don't know the proper orientation of bonds in a molecule cannot successfully determine the dipole moment of a compound. This lesson circumvents this by giving students ball and stick models that have the correct geometry. Because of time constraints, we chose not to spend time on learning how to determine geometry. However, even when provided with the geometry, students may find it difficult to understand how to 'see' the dipole across a molecule, especially tetrahedrals. We invoke two metaphors, the electric field method and the 'slice' method, to help students perceive dipole moments across a molecule.

Materials

Item	Number/Amount
Colored marshmallows (two colors)	4 of each color per pair of students
White marshmallows	4 per pair
Toothpicks	4 (cut in half) per pair
Sharp scissors or shears	1
Ruler	1 per pair
Ball-and-stick kit	1
Paper towel	1 per pair
Index cards	1 per ball-and-stick molecule

Cautions/ Potential Pitfalls

Provide already assembled example ball-and-stick models of the molecules in the lab. Stress to students that they have to make their models match the examples, especially in terms of the angle of the bonds. On another note, cutting the toothpicks in half allows students to create models of molecules that mimic space filling models, which might help alleviate the misconception that a bond is a line or a stick that holds atoms together.

Pre-Class Preparation

Getting the Materials Ready

Assemble the example ball-and-stick models before class. Ask students not to disassemble them.

Safety Issues

Students should not eat the marshmallows as this is taking place in chemistry laboratory and surfaces and hands may have traces of chemicals. Also most schools have no eating policies in academic rooms.

DOING THE LESSON

Opening

Teacher asks students to write HW answers on the board and leads students through a discussion of the correct answers. Make a point of focusing on the last question. It is easy for students to just focus on the calculations without really understanding what they represent.	

Activity 1 – Marshmallow Molecules Lab

Students take their homework molecules plus water and construct marshmallow molecules that are colored based on charge across	

the bond moment. They then predict how these molecules would interact with a charged object. The goal is to see how the presence of a bond moment doesn't always lead to the molecule interacting with a charged object. Tie this back to the Bending Liquids Lab. If students develop a notion that bond moments are additive, then they can add up these to create an overall dipole moment or see that the bond moments can cancel each other. Teacher should **create 6 to 12 stations** depending on time and resources. Each station should have **12 marshmallows** (4 of each color: pink, green, and white). These can be placed on a paper towel. Along with these marshmallows, include four toothpicks, which have been cut in half using scissors. Colored marshmallows can be found at the grocer store along with the toothpicks. Each station should also have a ruler. Each station or pairs of stations should have ball-and-stick models of the five molecules (placed on an index card with the formula or affixed with a sticker with the formula). Molecular geometry is crucial for determining dipole moments, and these models serves as references for students. After having kids find their lab stations, demonstrate how to do the lab with the first molecule, HCl. The Lewis structure with the bond moments should already be on the board. Ask students to build the model of the molecule. Have students compare their models with yours and discuss discrepancies. Stress that the molecules in the lab are to be treated as molecules. If they are normally a gas at room temperature, we will assume they have cooled and condensed into a liquid. Now ask students to imagine how the hydrochloric acid would line up with respect to a positively charged ruler. Remind them that it might not line up in a certain way. Tell students to take a minute to discuss and make a decision. Then have students share their choices and ask them to defend their choices. Note that the **slight** negative charge of the chlorine will be attracted to the positive ruler, whereas the slight positive charge of the hydrogen will be repelled. Repeat this with carbon dioxide. Note here that both 'sides' of the molecule have a negative charge, so the molecule won't line up but will rotate constantly	**Note** the molecules chosen are gases or liquids,which can rotate. See student materials for "Marshmallow Molecules Lab" Gases have too much kinetic energy to line up with respect to a weak electric field.

At this point, the teacher can have students finish the rest of the activity by themselves. Once students have finished, share answers and have students explain their reasoning. Critique where applicable.

Teacher Talk

After finishing the lab, teacher should conduct a teacher talk on dipole moment/molecular polarity.

"How did people determine if the molecule would line up? [Teacher should stress the difference between the first molecule, HCl, which has two 'sides', and CO_2, which doesn't (the positive charge is buried in between the two negatives). And use this notion of having two 'sides' of different charge as a way to distinguish substances. At this point introduce the notion of a dipole moment]

"So we can think of two types of molecules, those that have two sides, and which orient themselves to a charged object. And those that don't have any sides. In chemistry, we say that a molecule that has two sides, has a dipole moment. We also call this a polar molecule. But we have to be careful. A bond that is polar has a bond moment. But if overall, a molecule is polar, then it has a dipole moment.

Possible table:

Charge difference across the bond	Bond moment ~ polar bond
Charge across the entire molecule	Dipole moment ~ polar molecule

"So for example, HCl has a bond moment, here, [points to the bond] and a dipole moment.

"But **if a molecule has more than one bond moment, it doesn't necessarily have a dipole moment**. For example, carbon dioxide, has two bond moments. But the sides of the molecule are not different—they balance each other out. The positive center is surrounded by the negative oxygens.

"However, in some molecules, the bond moments don't cancel each other out. If they point in the same general direction, they add up to give the molecule an overall dipole moment. An example of this is ammonia, NH_3. The bond moments are all pointing towards the nitrogen, which makes the side with the nitrogen negative, and the side with the hydrogen atoms positive.

“Geometry is very important here. Because NH_3 looks like a pyramid, all of the bond moments point in the same direction. What if NH_3 looked like a Y would we it still have a dipole moment? [Draw a trigonal planar molecule and hold up physical model—one can use marshmallows if the ball-and-stick kits will not work],

-Students will struggle with this. Remind them to consider the Marshmallow Molecules Lab. How would such a molecule respond to the external charge. Are there any sides? Will it rotate rather than line-up with the field?

“So, it won’t be a polar molecule. Why? [**Because there aren’t two sides of different charge.**

“If you are confused, **imagine that you had a tiny knife that you could use to cut the molecule through its center into two pieces**. IF you can cut the molecule into two pieces, each with only one type of charge on its side, then you have a polar molecule. [Teacher uses hand to “cut” the HBr such that there are two sides (one positive and one negative).

“With carbon dioxide, we get two sides, but we have negative oxygen on both sides—to be a polar molecule we need a positive side and a negative side.

Homework

Have students practice on question 6 where they determine dipole moments for several additional molecules. The teacher may want to prepare a few ball-and-stick models of the molecules to help students see the geometry.

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DAY 8

LESSON OVERVIEW

Lesson Description

Students will use a series of simulations to visualize how polar molecules (dipoles) interact with charged particles, other dipoles, and nonpolar molecules. Today's lesson is meant to help students distinguish between interactions between: (1) charged atoms/molecules where electrons have been transferred from one to another (ionic), (2) neutral molecules that have a permanently unequal electron distribution (dipole-dipole) and (3) nonpolar atoms and molecules Additionally, students will explore how dipoles can induce a charge in neutral, nonpolar objects to become charged just as the balloon induced charge in the wall from before.

Learning Goals

5. Students will describe a polar molecule as having an asymmetric electron distribution, which leads to a charge imbalance across the molecule.
6. Students will distinguish between types of electrostatic interactions based on the magnitude of charge.
7. Students will be able to explain how there can be an electrical attraction via induction between nonpolar atoms or molecules and a dipole.

Teacher Background Content Knowledge

See Day 6.

Student Prior Knowledge Expectations

See day 6 and 7.

Potential Student Alternative Ideas

Some students may categorize intramolecular forces as being intermolecular in nature (Peterson 1989). Students also may not consider the dependence of the strength of forces on scale. They may believe that gravity plays a significant role in interactions on the molecular level and could counteract electrical intermolecular attraction (Coll 2001). In addition, see the alternative ideas discussed in days 4 through 7.

Potential Student Difficulties

Although electrical attractions between opposite charges are observed in static electricity and in dipole interactions, both the mechanisms and the magnitude of charges involved are different. In our exploration of static electricity, we noted that electrons are removed from or added to atoms to create ions. Because there was a complete transfer of electrons, the charges have an integer value. However, in dipoles electrons are not removed from the molecules but simply distributed unevenly. Because there is not a transfer of electrons, the molecules remain neutral but have some directionality to their electron distribution that leads to partially positive and partially negative regions. A second important distinction is that we dealt with charged objects when this unit covered static electricity, but dipole theory applies to individual molecules. However, induction of neutral objects and molecules occurs by the same mechanism for both static electricity and dipoles.

Materials

Item	Number/Amount
Laptop computer	1 per group
Capillary tubes	1
Tap water	Several small beakers full
Small beaker	1

Cautions/ Potential Pitfalls

As with any activity involving computers, check to see if the computers are working. An internet connection is necessary to access these simulations.

Pre-Class Preparation

Getting the Materials Ready

Try these simulations prior to class to make sure that any accessory plug-ins are already on the computers.

Safety Issues

N/A

DOING THE LESSON

Opening	Notes
Teacher asks students to write homework answers on the board and has them explain their answers. She then reviews what a dipole is (just a polar molecule), and how it arises from bond moments. Today, the teacher also promises to return to the geckos and how water lets things stick to walls. ***Demonstration***	

Show students a capillary tube (have several extras to pass around) and describe its structure. Ask students to predict what will happen when you put the tube in a beaker of water. Will the water go into the tube? If so, how far up? Ask students for the reasoning behind their predictions. Place several tubes in their own beaker of water and pass around for the class to see. On the board, sketch a drawing of the tube in the beaker, noting the level of water outside the tube and inside the tube. Remind students that water is 'sticky' because of its polar nature. Have them try to explain how water can climb up the sides of the tube. Ask them to speculate about the role of the atoms in the tube.	

Activity 1 – Dipole Simulations

Rationale: Students will use a software simulation to explore dipole-ion interactions, dipole-dipole interactions, and dipole-induced dipole interactions. **Simulation 1:** Have students go the following website: http://molo.concord.org/database/activities/43.html ***Suggested Answers for the Student Handout*** 1. What do the football shapes represent? What does the arrow represent? What is this arrow missing? [*The footballs represent simplified polar molecules and the arrow represents the charge distribution- of a polar molecule. Normally the arrow has a positive sign at one end.*] 2. Describe their behavior. [*The molecules wiggle around with their negative end always facing the positive point charge.*] 3. Explain their behavior. [*At room temperature, the molecules have kinetic energy, and so they wiggle around, but because of the attraction the negative dipole to the + point charge, they are only allowed to wiggle in such a way that maximizes attraction/minimizes repulsion. Therefore, these*	See student materials entitled "Dipole Interactions." If students do not already begin to modify temperature, ask them to do so.

molecules vibrate with their negative dipole facing the positive point charge. However, if heat is added to the system, the molecules gain kinetic energy to move independently of the electrical forces.

4. What about the simulation would change if the charge at the center were negative instead of positive?
[*The molecules would flip orientation such that the positive dipole was facing towards the center negative point charge. Otherwise the simulation would be the same.*]
5. How does the term polar molecule relate to this simulation?
[*The football with its +/- signs IS a polar molecule. We could replace the +/- signs with the +→ sign. The arrow would be on the end with the negative sign.*]
6. What is the difference between the positive inside the 'football' and the positive inside the circle?
[*The difference is a matter of degree. The positive in the dipole is only partially positive (less than +1 but greater than zero). The positive sign in the circle is fully positive.*

Simulation 2

Have students go to the following website:

http://web.mst.edu/~gbert/INTERACT/intermolecular.HTM

This is a website that shows how different types of molecules interact with each other. It is not interactive, but rather shows small ongoing clips of molecular motion. Students will visit the links in the table below and write a short observation of what they see.

Note: The site color codes negative as pink and positive as blue.

Suggested Answers for the Student Handout

Analysis

Type of Dipole Interaction	How does Charge Change?*	Cause of Interaction
		One end of the dipole is attracted to the oppositely charged ion.

1. Ion-	No change	One end of the dipole is attracted to the oppositely charged ion.
Dipole	No change	
2. Dipole-	No change	One end of the dipole is attracted to opposite charged end of another dipole.
Dipole	No change	
3. Dipole –	No change	One of the charged ends of the dipole changes the distribution of electrons in the nonpolar molecule
Induced Dipole (with a nonpolar molecule)	Symmetrical elecron density (no regions of charge) to a dipole	

In the last interaction, explain in your own words why it is called an‘induced dipole’.
[*The nonpolar molecule is originally neutral. But when the dipole comes near it, the charged end of the dipole attracts or repels electrons in the nonpolar molecule. The side of the nonpolar molecule where electrons move to becomes negative because electrons are slightly negative, whereas the side that lost electrons becomes slightly positive.*]

How do the three interactions differ from each other?
[The first two do not involve any change in the distribution of electrons and hence charge. The only difference between them is whether one of the particles is an ion or a dipole. Ions have lost or gained electrons and thus have a full positive or negative charge. However, dipoles are neutral over all, though they have a partially negative and positive region due to unequal sharing of electrons. The last interaction differs from the first two in that the nonpolar object becomes polar (electrons are not equally distributed) as a result of interacting with a dipole. As a result, regions of partially negative and positive charge arise temporarily.

Rank the three interactions in terms of the strength of the force

As you walk around or later in whole group discussion of the simulations, ask students if the induced dipole, the nonpolar molecule that became charged, has a fully positive or negative charge or if it is partially positive and negative. [It's the latter option.]

One might want to remind students about water's geometry and polar character by sketching a picture on the board. For less support, can

of the interaction from strongest to weakest. Explain your choice. [Ion-dipole > dipole-dipole > dipole>induced dipole *The first involves a permanent, fully charged ion with a dipole. Since the charge is larger, the strength of the force will be larger. The dipole-dipole will be weaker since the charges involved are only partially positive or negative. Finally, the weakest will be the dipole-induced dipole since the nonpolar substance has to be induced to have a charge. The positive and negative regions that arise will be very weakly charged.* Which type of dipole interaction is the way wet paper sticks to a wall? Assume the wall is a neutral, nonpolar surface. Explain. [*Water is a polar molecule and the surface is nonpolar, therefore it is dipole-induced dipole]* Draw picture of how water sticks to a wall. Include sketches of before and after water sticks [*Students should have a before drawing in which the atoms in the wall have a uniform electron distribution (nonpolar) and water is polar. The after drawing should show that the atoms in the wall have become partially charged from induction. This charge should be opposite of the charge on the atoms in the water molecules*. The molecules of water need not be aligned in the same direction.] How would the interaction with water be affected by making the wall polar? Explain. [The interaction would be stronger i.e. the water would be more strongly bound to the surface.] Compare the interaction of water between a polar and a nonpolar surface. Sketch in columns in the blank graph below. [The force between the polar water and the polar surface should be higher than that between water and the nonpolar surface.]	simply direct students to the previous days lab sheet.

Homework

Give students ample time at the end of class to begin working on interpreting the data.

Work was done to see if the type of surface the gecko stuck to matter. Gecko foot hairs (setae) were removed and placed on two different surfaces: one polar and one nonpolar. The hair was connected to a microforce gauge (analogous to a spring scale). Then the amount of force required to remove the seta was determined. Students are asked to predict what they would see if geckos used water to stick to a surface. They then compare the predictions with the results and produce an argument.

References

Coll, R., & Taylor, N. (2001). Alternative conceptions of chemical bonding held by upper secondary and tertiary students. Research in Science and Technological Education **19**: 171-191.

Peterson, R., Treagust, D., & Garnett, P. (1989). Development and application of a diagnostic instrument to evaluate grade-11 and -12 students' concepts of covalent bonding and structure following a course of instruction. Journal of Research in Science Teaching **26**: 301-314.

DO GECKOS STICK BECAUSE OF LONDON DISPERSION FORCES?

DAY 9

LESSON OVERVIEW

Lesson Description

In this lesson, students will use a simulation involving dice and M & M's to simulate a probability model of electrons in a nonpolar covalent bond. From this simulation, they will see that random fluctuations in electron density can produce transient dipoles in nonpolar substances. These then induce dipole themselves.

Learning Goals

1. Students will describe electron behavior by noting that we cannot know the path of an electron but rather can only predict with the probability of where it might be.
2. Students will explain London dispersion forces by citing that non-uniform distributions of electrons occasionally arise leading to momentary dipoles.

LESSON PREPARATION

Teacher Background Content Knowledge

About 1970 it was clear that adhesion is the answer to the question of how the gecko sticks to the wall or ceiling, but it was not clear whether capillary forces or van der Waals forces are the main contributor to gecko adhesion.

As was discussed before, gecko adhesion occurs in experimental scenarios when capillary forces should fail to occur, indicating that capillary action is not sufficient to explain gecko adhesion.

In addition to the force measurements discussed in Lesson 7, Autumn *et al*. also measured how hydrophobic the setal surface directly, by placing water droplets on the seta-bearing toe pads. Hydrophobic refers to whether a substance repels water; nonpolar substance do not interact with water as the polar water molecules prefer to interact with each other through hydrogen-bonding.

Here is an example of a hydrophobic blade of grass:

Figure 20 Water droplet on grass blade (http://en.wikipedia.org/wiki/Image:Dew_2.jpg - courtesy of Michael Apel).

Autumn and his colleagues found that gecko setae are strongly hydrophobic. This result and the results of the force measurements taken earlier (see Lesson 7) show that gecko adhesion occurs when two hydrophobic surfaces – the gecko's setae and the GaAs/Si wafers – are brought together. The only intermolecular force that explains hydrophobic/hydrophobic (nonpolar-nonpolar) attraction is the London dispersion force.

A note on van der Waals and London dispersion forces

All electrostatic forces get weaker as the distance of the two objects (atoms or molecules) is increased. The forces due to interaction between

1) two permanent dipoles
2) a permanent dipole and the induced dipole caused by it
3) neutral atoms or molecules, e.g. inert gases

all drops of as r^{-7}. Because they are so dependent on distance, they only become important when two objects in very close proximity within a few atomic radii. This group forces are known as *van der Waals* forces. In contrast to the first two, the latter is always present and therefore plays an important role in many phenomena such as adhesion, surface tension, properties of gasses and liquids, structures of proteins and polymers. One very important phenomena addressed in this unit is capillary forces. Capillary forces are the result of the first two interactions of the van der Waals forces. The last interaction, which is always present between neutral molecules, was first treated quantum mechanically by London, who used the term *dispersion forces* to describe them. Today we refer to them as London dispersion forces (though some textbooks use the term van der Waals forces to describe what are really only London dispersion forces).

We will here give a brief description of how the London dispersion forces come about. Imagine a neutral atom such as Argon, the time averaged electron cloud surrounding the positive nucleus is fully symmetric. But the electron cloud fluctuates, so a snapshot of the cloud would show us an asymmetric cloud, i.e. at the very moment the snapshot was taken the Argon atom had a dipole moment. A moment later a new snapshot will show a dipole moment pointing in a different direction, so over a macroscopic span of time, the dipole moments will average out. The instantaneous dipole moment may induce a dipole moment in a neighboring Argon atom, and the interaction between the dipole moments attracts the two Argon atoms. Note that the London dispersion force is *not* an interaction between *two* snapshot dipole moments, as half of the time the interaction between the dipole moments will be attractive and half the time repulsive.

Student Prior Knowledge Expectations

Students should have some knowledge of probability. They should recognize that the probabilities are multiplicative. For example, the chance of two events happening together is less than the chance of them happening independently. So I have a 1-in-6 chance of rolling a 1 on a die, I have 1-in-36 (1/6 x 1/6) chance of rolling two 1's at once. Students should also be familiar with the concept of an electron cloud and have some sense that our current models cannot predict the location and velocity of an electron, but rather offers probabilities of where the electron is likely to exist.

Potential Student Alternative Ideas

Little research has been done on students' ideas concerning London dispersion forces or van der Waals forces Other research suggests that some students consider bonding (ionic and covalent) to be different ('interactions' or 'attractions') from dipole and London dispersion forces.

Potential Student Difficulties

A probabilistic model of electron density is difficult for students to understand. Moreover, many simulations and representations of electron behavior are not probabilistic and reinforce the misconception that electrons follow orbits or predefined paths. We try to simplify the probabilities involved by using dice, though this can introduce misconceptions about the relative frequency of London dispersion events. However, we try to prevent the development of those misconceptions by having students interrogate the simulations and its assumptions.

Materials

Item	Number/Amount
A die	1 per group of 3 students
M & M's (same color)	2 per group of 3 students
Iodine Molecule diagram	1 per group of 3 students
Small container of iodine	1

Cautions/ Potential Pitfalls

You can replace the M & M's with something else that is small and round in case you are concerned students will eat the candy. One might collect the dice at the end of the lab to thwart theft.

Pre-Class Preparation

Getting the Materials Ready

If the teacher chooses, he can assemble lab kits with the items above.

Safety Issues

N/A

DOING THE LESSON

Opening

Teacher has students present conclusions about the graphs and their arguments about whether geckos use water to stick. Teacher starts the lesson with a ray of hope. Tell the class there is another form of attraction that could be used by the gecko for adhesion. They will spend today and tomorrow learning about this type of adhesion.	

Teacher Talk

Teacher leads the class in a discussion about London dispersion forces (LDPs). This is an introductory lecture to support the activity that follows. Teacher begins with some talk about nonpolar-nonpolar interactions. "Let's say we have a non-polar molecule. Like iodine, for example. A quick review: why is I_2 non-polar? [If students are slow to respond, ask them about the bond moment of the I-I bond and its geometry]. What does non-polar mean? [equal sharing, but more importantly no charge separation—no charged 'sides' to the molecule] "So if we had two I_2 molecules, would they be attracted to each other? What would be the source of the attraction? Why wouldn't they be attracted? "So we would predict that if we had two I_2 molecules they wouldn't be attracted to each other. Let's say we had we had 5 I_2 dimers. How would they interact with each other? [Number shouldn't change anything-they should still not be attracted to each other] "So, what would you predicate would be the state of a sample of I_2—will it be a gas, a liquid, or a solid? [attractive forces are greatest between solids, less so for liquids, and least for gases] "Let's see what state iodine is in. [Teacher then shows solid iodine—if small sealable flask is available send samples around for students to see up close. "Iodine at room temperature is a solid. This implies that there are attractive forces between the iodine molecules. How could this occur? "It looks like we have a situation we need to explore further. But	**Rationale**: The mechanism for gecko adhesion is LDPs. But integral to understanding these forces is having a sense of the probabilistic model of electron density. Research on wait time suggests pausing for 5 to 10 seconds can improve response rate. The goal here is not to answer the question oneself, but to get students to ponder the question and share their initial thoughts.

<table>
<tr><td>maybe the way the iodine molecules stick together is the same way that a gecko sticks to a wall. By exploring how these molecules we may find the answer we have been looking for.”</td><td></td></tr>
</table>

Activity 1 – Electron Density and Instantaneous Dipoles Simulation

<table>
<tr><td>Teacher should prepare 6 to 12 stations. Each station should have a die, two M & M’s, and a photocopy of the iodine dimer diagram from the student materials. The instructions are largely self-explanatory, but the teacher may choose to run through one simulation of the lab with the entire class to ensure fidelity.

The word instantaneous is used in the lab; it may be helpful for the teacher to define this word and use it in a sentence before the lab gets underway.

During the lab students will be asked to label each instance as having a dipole or not. In order to reduce the frequency of dipoles, the designers of this simulation chose the following rule: if BOTH the electrons are close to one atom (both are in the ‘1’ and/or ‘2’ position or ‘5’ and/or ‘6’ position), then this would be classified as having a polar character. This is an arbitrary decision. However, recognize that if you change the rule, you will either decrease or increase the occurrence of dipoles. Increasing the occurrence (for example, changing the rule to “BOTH electrons in the 1,2, or 3 positions or BOTH in the 4,5, or 6 position”) may lead to the misconception that instantaneous dipole arise frequently. Decreasing the occurrence would better reflect reality, but might require more simulations and would lengthen the time of the lab.

Whatever the rules ultimately are in this simulation, students should create drawings of the dipole to highlight the similarity (at least in charge imbalance) between a permanent dipole and an instantaneous dipole. Students could use egg shapes to note the shape of the electron cloud.

Suggested Answers to the Analysis Questions:

1. How does it arise?
[Random fluctuations in electron density create imbalances that lead to a temporary charge imbalance. This imbalance is what produces the instantaneous dipole.]
2. How common is it for an instantaneous dipole to arise in a nonpolar bond?
[The number will vary randomly. It is crucial for students to</td><td>See student materials entitled: “Electron Density and Instantaneous Dipole Simulation”

The teacher may want to go over the iodine dimer diagram and note that the circles represent the iodine nuclei. Stress also that the only electrons represented are the ones in the bond, BUT that many other exist—iodine is atomic number 53. We are simplifying matters.

Remember that London dispersion also acts on any bond including permanent dipoles and so may occasionally reduce the strength of the permanent dipole by reversing the electron distribution. This is a subtlety, though.</td></tr>
</table>

realize that dipoles do arise randomly. However, the teacher should stress that the chances of finding a dipole that are used in this simulation are much higher in reality. The teacher will return to this point later.]

3. What are differences between an instantaneous dipole and a dipole in a polar molecule?

[There are two differences. The first is with respect to time. A normal dipole has a “permanent” dipole i.e. the imbalance in charge is on average always present. Students should recognize that non-polar bonds can randomly have imbalances in electron density that produce temporary dipoles.

The second difference concerns how the dipole is created. In a permanent dipole, the nuclear charge and shielding effects of the bonded atoms lead one of the atoms to have a greater affinity for electrons i.e. a greater electronegativity. This leads to an imbalance in the distribution in electron density between the two atoms. Since the atoms in the bond don’t change, these differences in electronegativity are always present and result in a permanent dipole. For an instantaneous dipole, both the bonded atoms have the same or nearly the same electronegativity. Rather the dipole here arises from random fluctuations in electron density.]

See Teacher Talk after this simulation.

Many of these caveats are embedded in the directions. If students need additional support, suggest they read the directions again.

4. During the moment when the instantaneous dipole exists, what effect does it have on neighboring nonpolar molecules? Explain.

[It induces them to have a charge. But since the instantaneous dipole has a weak charge, it also induces a weak charge in its neighboring molecules.]

5. What are the limitations of this simulation of electron behavior?

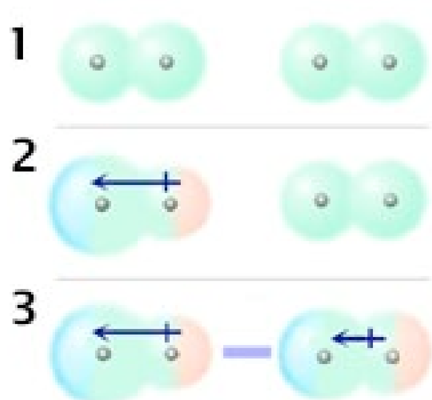
[Electrons don’t stick to a line but reside in three-dimensional space and they also don’t have only 6 states (as determined by the die). Additionally, we only kept track of two electrons. In an atom like iodine, there are far more electrons involved. Students probably won’t mention this, but the iodine has such strong shielding that its electrons are less tightly held to the nucleus and thus can be polarized much more easily. Finally, the simulation and its rules for determining when a dipole occurs creates a misimpression that an instantaneous dipole frequently arises in a molecule—in reality, instantaneous dipole are rarer.

Teacher Talk

What follows is an example of a lecture:
"Class, let's talk about question five together. This is crucial to our understanding. I am going to draw three iodine molecules like before. Now we established from this simulation that occasionally electrons accumulate on one side of the bond leading to an instantaneous or temporary dipole. So let's redraw the middle iodine molecule as if it were undergoing this temporary charge imbalance. We will keep the other iodines non-polar because the chances that both of these would turn into an instantaneous dipole at the same time is quite small.

"At this point in time (and it isn't for very long), we have a dipole here. So will anything happen to this nonpolar molecule across from it? [if students don't respond, direct them back to the previous days activities and the lab sheet]

"Don't forget that induction is always an option. The middle molecule induces a charge difference in the other two. Let's draw what that would look like.



"But to do so they have to be very close to each other. Also remember these are very transient, so what arises also disappears in a short matter of time. The force between the two is weak as a result, weaker than any of the forces, electrostatic or permanent dipole, that we have thus far studied. Yet, it is enough to cause iodine to form a solid. Chemists have a special name for this weak force—it's called the London Dispersion Force after the man who first theorized it.

[Students may ask how such a weak force that is only there for a fraction of time can keep iodine together in a solid state. One response, which is the subject of tomorrow's lesson, is to stress that though instantaneous dipoles arise infrequently, there are

Iodine also has a very large electron cloud with electrons that are held less tightly than in other elements. Thus, the electrons in iodine's outer shells are more polarizable.

trillions upon trillions of iodine dimers in a sample, so that at any point in time there are many instantaneous dipoles occurring. Students should also remember that a solid is three-dimensional and that the instantaneous dipole is inducing dipoles in many of its neighboring molecules. Finally, iodine is a really heavy molecule so at room temperature its molecules are moving at a slower speed than lighter molecules under the same conditions. Since it is moving so much slower, the millions of weak London dispersion forces are enough to crystallize it.]

Additional examples:
You could discuss another non-gaseous nonpolar molecule, for example, bromine, or one of the alkanes, say pentane. Regardless review the formation of the instantaneous dipole and induction in neighboring molecules.
If you have time, you could also look at trends associated with LDFs.
One could look at the boiling point trends for the halogens

F_2	-188°C
Cl_2	-34.4
Br_2	59
I_2	184

Though London dispersion occurs with all of these, it less frequently arises in the smaller diatoms because of stronger effective nuclear charge. The big atoms have large electrons clouds with much shielding, so the valence electrons are less tightly held and therefore more likely to polarize on occasion.

However, you might want to show students a trend in organic alkanes.

Alkane	State at 25°C	Boiling Point (°C)
Methane	Gas	-162
Ethane	Gas	-89
Propane	Gas	-42
Butane	Gas	-0.5
Pentane	Liquid	36
Hexane	Liquid	69
Heptane	Liguid	98

These are all nonpolar molecules and the London dispersion forces are too weak at room temperature to condense the smaller molecules (methane to butane), but once the molecules reach a certain size they become liquids at room temperature. This is thought to occur because the chances of having an instantaneous dipole increase with the number of electrons in the outer shell. Also the linear nature of these molecules (we'll ignore their

branched isomers) allows that charge to propagate along the molecule, increasing the stability such temporary polarization. Students may belief it is just mass, but there are several gas molecules with larger formula masses than pentane. For, example, gaseous sulfur trioxide, a common pollutant has a MM of 80g/mol, whereas pentane only has a MM of 72g/mol. Don't forget that many of the heavier noble gases have large MMs as well. Therefore, something else is at work besides mass.	

Homework

How could a gecko use London Dispersion forces to stick to a ceiling? Walk through this process step-by-step. Please provide a drawing with your brainstorming.

References

Autumn, K., Sitti, M., Peattie, A., Hansen, W., Sponberg, S., Liang, Y. A., Kenny, T., Fearing, R.,Israelachivili, J., and Full, R. J., *Proceedings of the National Academy of Sciences of the U.S.A.* **99**, 12252-12256 (2002).

Taber, K. (2001). Shifting sands: a case study of conceptual development as competition between alternative conceptions. International Journal of Science Education **23**(7): 731-753.

DO GECKOS STICK BECAUSE OF LONDON DISPERSION FORCES?

DAY 10

LESSON OVERVIEW

Lesson Description

Students compare and contrast static electricity, dipole interactions, and London dispersion forces. They then relate the anatomy of the setae to London dispersion forces to argue for a mechanism of adhesion that utilizes these forces. Using a series of conversion factors, they determine the number of spatulae (the tiny projections on the setae) required to lift up a gecko and their own body weight. These last calculations demonstrate that London dispersion forces can be significant despite their weak strength if the number of contacts with the surface are high. Finally, the students construct as essay in which they review the various evidences and provide an argument for how geckos stick to ceilings.

Learning Goals

1. Students distinguish between the relative strengths of the various intermolecular interactions using the magnitude of charges involved and the permanence of this charge.
2. Students explain how relatively strong forces of attraction can be achieved by London dispersion forces alone, and apply it to the case of the gecko with the surprisingly large amount of contact area that occurs between the spatulae and the wall/ceiling.

LESSON PREPARATION

Teacher Background Content Knowledge

See Day 9.

Student Prior Knowledge Expectations

Students would benefit from having some experience with dimensional analysis in performing the conversions in this lesson.

Potential Student Alternative Ideas

See Day 9.

Potential Student Difficulties

See Day 9. In addition, conversion calculations can be difficult for students to perform.

Materials

Item	Number/Amount
Gallon of drinking water	1
Rubber bands (two different thicknesses—one should be thick enough	Enough to hold up the gallon of water

to support the jug by itself—see the rubber bands placed around broccoli)	
Coat hanger	1
Wire cutter	1
Broom handle or ring stand	1

Cautions/ Potential Pitfalls

N/A

Pre-Class Preparation

Getting the Materials Ready

Cut the coat hanger and loop the cut ends around the handle of the gallon jug, keeping the hook of the hanger free to connect rubber bands to. Test to see how many of the thin rubber bands are needed to hold up the jug of water.

Safety Issues

N/A

DOING THE LESSON

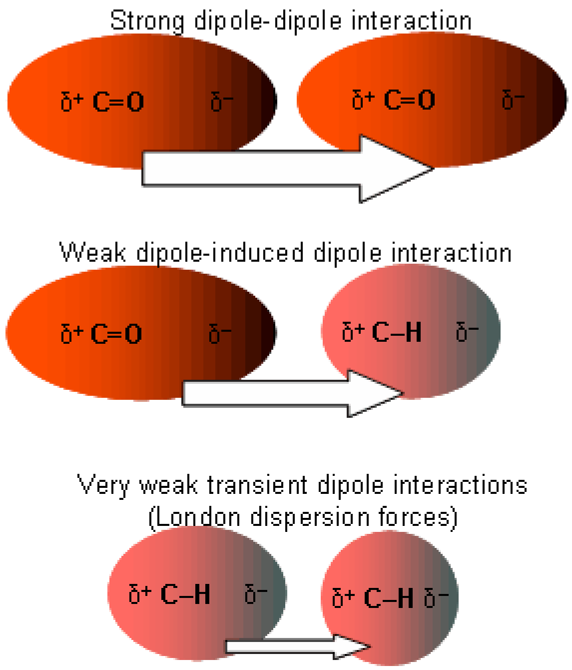
Opening	Notes
Teacher begins lesson by discussing homework with students. Teacher reviews how instantaneous dipoles occur and how London dispersion forces arise through induction between instantaneous dipoles and neighboring nonpolar molecules.	

Activity 1 – Stickin' Spatulae

<table>
<tr>
<td>This is the final activity of the unit. Students distinguish between the types of interactions and then integrate their understanding of London dispersion forces with the anatomy of the gecko footpad.
For the worksheet, one might stop the students half way and discuss question 6 and run the demonstration detailed below.
Suggested Answers
1. Arrange the above forces in order from weakest to strongest
Weakest Strongest
<table>
<tr><td>London Dispersion Forces</td><td>Dipole-Induced Dipole</td><td>Dipole – Dipole</td><td>Dipole – Ion</td><td>Static Electricity</td></tr>
</table>

2. Explain why you chose that order.
[Static electricity and the dipole interactions involve molecules/objects that are charged to some degree over time. But the LDFs are only momentarily</td>
<td>See student materials entitled “Stickin' Spatulae.”</td>
</tr>
</table>

charged. The different dipole interactions are weaker than static electricity because they involve partially charged species. Within the dipole interactions, the strength is also based on magnitude of charge: the ion has a fully positive or negative charge, followed by the dipole with a partially positive charge, and the nonpolar molecule, which is neutral initially.]

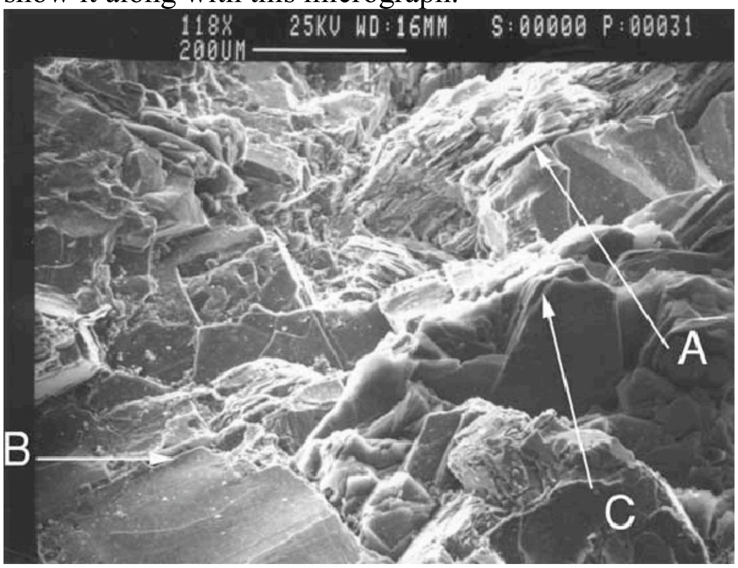


3. Contrast the above forces in terms of the value of charge involved and the permanence of the charge.

Type of Interaction	Value of Charge	Permanence of Charge
London Dispersion Forces	Partially charged	Temporary
Dipole- Induced Dipole	Partially charged/originally neutral	Permanent/temporary
Dipole – Dipole	Both are partially charged	Permanent
Dipole – Ion	Partially charged/fully charged	Both are permanent
Static Electricity	Fully charged particles	Long lasting

4. How does the distance between molecules/objects affect the forces above? For example, if I were to take two molecules and separate them slowly, what would happen to the attraction between them?
[*As the distance between molecules or objects increases, the force decreases.*]
5. London dispersion forces are only significant when two molecules (or the two surfaces that are made of these molecules) come in very close contact. Does a gecko's foot (see picture below) allow for this kind of

contact?
[Even surfaces that are smooth to the naked eye are actually very rough when magnified enough. There are lots of NANOSCALE cracks and crags on the apparently smooth surface. The tiny spatulae on the gecko feet are only 200 nm in diameter so they are able to make direct contact with the all the nanoscale surface features of the granite.]
Here is an example of a micrograph of a polished granite countertop. If you have a granite cutting board at home, you might want to bring it in and show it along with this micrograph.



An analogy that might be useful: gecko setae remind people of tiny brushes. One could ask students whether it would be easier to paint a surface with a paintbrush or with a stick. The brush is better because the individual hairs of the brush can get into the grooves of a surface and deposit paint evenly. A stick would miss those cracks.

6. London dispersion forces are the weakest of the intermolecular forces. How could a gecko use a weak force to hold itself to the ceiling?
[*Students need to recognize that adding together a large number of weak forces creates an overall strong adhesive force. So even though the attraction between each of the spatulae (the tiny projections on each seta) and a surface is very weak, if we have many, many spatulae touching a surface, the sum of the forces results in a strong attraction.*]

DEMONSTRATION:
You can illustrate question 6 by using a gallon of water, a coat hanger, and some rubber bands of different sizes. Attach the coat hanger as shown in the front materials of this lesson. Pick up the clothes hanger with the thick rubber band and see if it holds. Have extra rubber bands to pass around class so they can see what you're working with.
Ask students to predict what will happen with a thin rubber band. Then show students that a thin rubber band fails to hold. Beware of the rubber band when it breaks.

Next, tell students to take a second and figure out how to lift the jug assuming that they only had the thin rubber bands.
The answer will probably be obvious to many students—just connect multiple rubber bands between the hook and the broom handle.
One could start out with a large number of bands, a number that you know will hold, and then progressively reduce the number to find the minimum number of bands needed or visa versa—start small and keep breaking.
7. Using the following conversions, determine how many spatulae, the tiniest projections at the end of a gecko foot hair (setae), would be needed to hold a gecko up. A Tokay gecko weighs about 43g.
1 kg requires 9.8 Newtons (N) of force
Each spatula holds up 0.4 μN $1N = 10^6$ μN

The contact area is actually less than this if we were to zoom in to the surface, but as a demonstration of the point, this analysis works.

8. How many spatulae would be needed to hold up a Tokay gecko? How about you? (1 kg = 2.2 lbs)

9. If there are roughly 100 spatulae per setae (in reality the number varies between 100-1000) and there are approximately 530,000 setae per cm^2, how large a surface would be needed to hold your mass up?

10. The area of a human hand is roughly 120 cm^2. How many hands covered with setae would you need to be able to walk on the ceiling?

[One could hang by one hand, assuming that all the spatulae adhered. This is not the case for geckos (only 0.3% of spatulae adhere at a given time), and so we would presumably need a larger surface area.
11. We know because of fingerprints that human hands come into contact with surfaces. We showed yesterday that LDFs arise between any two surfaces. Yet, humans can't climb walls with their hands. Consider the fingerprint below and our knowledge about gecko setae, and explain why humans cannot stick to walls using our hands. The magnified region has 20 x 20 grid overlayed onto it.
[Students can count the white squares (no contact) and the black squares (contact) to figure out what percent of finger tip area is actually in contact with a surface. So even though one's finger is pressed against a surface, only a fraction of the surfaces are really in contact. Humans can't stick to walls, not because they don't have any LDFs between the surface and their hands. Rather there are too few LDFs because there isn't enough contact area.

12. Nanoscience is interested in manufacturing artificial setae to use as dry adhesives. The picture below is a micrograph of a new type of tape that is being tested as an alternative to stitches in surgery. Why do surfaces like the one above allow for strong adhesion?
[The tiny projections allow for greater contact between surfaces. Since LDFs are only significant when surfaces are in very close contact,

increasing the contact area increases the adhesive force. The photo below ties questions 10 and 11 together. It is an action figure with the man-made 'gecko tape' applied to one of its hands.  Picture taken from *Gecko inspires sticky tape* by R. Black (http://news.bbc.co.uk/2/hi/science/nature/2953852.stm, http://newsimg.bbc.co.uk/media/images/39106000/jpg/_39106516_spider_nature_203.jpg)	

Essay

Reserve the last twenty minutes of the lesson to have students write their cumulative essay on gecko adhesion. They may consult the summary of research to write the essay. See student materials entitled "Final Essay".