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Science, Technology, Engineering, and Mathematics (STEM) Activities on a Budget: Part IV. Adhesives

by R A Pesce-Rodriguez and A Rodriguez

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Science, Technology, Engineering, and Mathematics (STEM) Activities on a Budget: Part IV. Adhesives

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14. ABSTRACT

In Part IV of a series of hands-on science, technology, engineering, and mathematics (STEM) programs for K–12 students and of general interest for adults, we provide background information and specific guidance on materials and procedures for eight activities related to adhesives. All activities are designed to be executable with minimum expense and hazard. The program was developed as part of our ongoing "Chemistry in the Library" program, but is also appropriate for traditional and home school programs and museum classes. Background discussion includes key information about the composition, chemistry, and history of adhesives.

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Contents

List of Figures

1. Introduction

1.1 National Chemistry Week: Sticking with Chemistry!

The content of this report was prepared in anticipation of the American Chemical Society's (ACS's) 2020 National Chemistry Week program, the theme for which is "Sticking with Chemistry!: The Chemistry of Glues and Adhesives". For the past 18 years, we have been running hands-on National Chemistry Week and Earth Day programs for students and their caregivers in public libraries in Maryland. Because of the ongoing COVID-19 pandemic, our live programs are going virtual. The objective of this report is to provide background information on the fascinating topic of adhesives, as well as details on activities related to adhesives that will help demonstrate some important adhesive-related phenomena. It is anticipated that caregivers of our program participants and perhaps teachers (traditional or homeschool) might use this resource for their students to follow up on their virtual library program experience, or use the content independent of the library program.

As with other reports in this series on forensics, paper, and sand (Pesce-Rodriguez and Rodriguez 2019, 2020a, 2020b), the activities are intended to be executable on a budget and, to as great an extent as possible, with readily available materials.

1.2 Difference between Glue and Adhesive

Let's start off by defining what an adhesive is. According to Kinloch (1987), an adhesive is "any non-metallic substance applied to one or both surfaces of two separate items that binds them together and resists their separation". So, staples can bond paper together and rivets can bind sheet-metal surfaces, but neither staples nor rivets are adhesives because they are made of metals.

Most students are more familiar with the word "glue" than "adhesive". What's the difference? A glue is basically an adhesive that thickens with time, usually because of the evaporation of a solvent. For example, school glue is an emulsion of polyvinyl acetate in water. The glue thickens as the water evaporates and becomes clear as the glue completely dries. Nitrocellulose in acetone (similar to nail polish or "liquid bandage" formulations) thickens as the acetone evaporates and can function as a waterproof adhesive.

1.3 Brief History of Adhesives

Humans have been using adhesives for a long, long time. As far back as 40,000 years ago, Neanderthals used birch bark tar to glue stone to wooden handles (Mazza et al. 2006). In ancient Egypt, natural adhesives were used to attach inlays to furniture (Packham 2003). Natural products used in adhesives included starch, blood, collagen extracts from animal bone or hides, milk protein, and fish skin extracts. Even in World War I, airplanes were glued with adhesives made from dried animal blood (which is mostly protein). Synthetic adhesives only became common in World War II (Lambuth 2003). Over the course of the past 75 years, adhesives have continued to be developed and improved, and are essential to many aspects of our lives.

1.4 Uses of Adhesives and Common Adhesives

So what do we use adhesives for? Here is a list that we put together. Students, caregivers, and instructors can certainly add to the list.

- Stamps
- Labels (bottles, barcodes, address)
- Wall paper
- Laminates
- Crafts
- Post-it notes
- Band-Aids, medical patches
- Tapes (masking, duct tape, Scotch tape, surgical tape)
- Iron-on patches
- Shoes
- Furniture
- Toys
- Repairs
- Packaging
- Automobiles
- Construction (drywall, tiles, molding, floors)
- Airplanes
- Spacecraft

The following are some common adhesives:

- Elmer’s glue (polyvinyl acetate)
- Glue sticks (acrylic polymer)
- Crazy glue (polycyanoacrylate)
- Gorilla glue (urethane polymer)
- Hot melt adhesives (ethyl vinyl acetate copolymer)
- Nitrocellulose-based adhesives
- Epoxies
- Rubber-based adhesive
- Natural products
  - Starch glue
  - Animal glue
  - Milk glue
  - Blood glue

1.5 How Do Adhesives Work?

Now that we have some general background on what adhesive and glues are, gave a brief summary on why adhesives are important to us, described what types of adhesives are available, and provided a brief history of the human use of adhesives. We next focus on how adhesives work.

According to Hon (2003), a good adhesive needs to be a high-molecular-weight polymer that can carry and transfer mechanical force when in its final state. Let's think about what this means. We start with the part about "its final state". Most adhesives start out as liquids because they need to flow and penetrate into a substrate. Some adhesives are fluids because they are glues (remember that a glue is an adhesive in a solvent like water or acetone). Once glues dry, they are in their "final state". Other adhesives, like epoxies, come in two parts that must first react with each before reaching their final state; others, like some polyurethanes, need to react with moisture in the air to reach their final state. Both epoxies and polyurethanes react to form "high molecular weight polymers", a point mentioned by Hon as being important for a good adhesive.

What is a polymer and what does "high molecular weight" mean? The answer to these questions could be the subject of its own report or book, so we give a simple answer appropriate for young children here. We start with the basics. Everything around us and in us is made of matter. All matter is made up of elements. (Students may have seen a periodic table that includes all the known elements.) The simplest form of an element is called an atom. Atoms come together to make molecules. For example, hydrogen and oxygen are elements. When two hydrogen *atoms* join with one oxygen *atom*, they form a water *molecule*. Some molecules can react with other molecules to form larger molecules. For example, two sugars, glucose and fructose, can react to form sucrose (table sugar). Some molecules can react with other molecules and grow into very, very long molecules. For example, ethylene (made up of two carbons and four hydrogens) can react to form a long molecule called polyethylene. "Poly" is a word that come from Greek and means "many". So a polyethylene molecule can be thought of as a "many ethylene" molecule. If we think of an ethylene molecule as a bead, then a polyethylene molecule would be like a necklace with many beads.

Ethylene is considered a "monomer" ("mono" comes from Greek and means "one"). If two ethylene molecules react, they can form a dimer (a "two-mer"!). If three react, they will form a trimer (a "three-mer"), and so on. So, when we talk about a "high molecular weight polymer", we mean a molecule made up many, many monomers to make up a long molecule called a polymer (a many-mer). When polymers are very long, we can say they have a “high molecular weight” because their mass goes up with every monomer added to the chain.

We should now have an idea of what is meant by an adhesive’s “end state” and what a “high molecular weight polymer” is. Next, we need to think about the idea of the polymer being able to “carry and transfer mechanical force”. For this, it may help to think about the relative strength of a pile of loose Lego bricks compared with the same number of bricks connected together into a single structure. As the structure gets larger with the addition of bricks, it is better able to “carry and transfer” a load or a force.

Assuming that students understand what an adhesive is, we now move on to how adhesives work. Hon (2003) states it simply: “**flow, penetrate, wet, set**”. This means that an adhesive must be able to do the following:

1) **flow**, meaning that it can spread out on a surface. This might mean that the adhesive is a high-molecular-weight polymer in a solvent (a glue) or a hot melt glue that has been heated, or a substance that is composed of small molecules that are fluid to start with and then react to form high-molecular-weight polymers.

2) **penetrate**, meaning that the substrate is porous enough to allow the fluid adhesive to seep into pores or surface defects or other irregularities.

3) **wet**, meaning that the fluid adhesives are made up of chemical groups that are attracted to the substrate. As we see in in this program, some substrates are not attracted to most adhesives.

4) **set**, meaning that the solvent in a glue will dry and that molecules that need to react to form high-molecular-weight polymers will do so. Small molecules do not make good adhesives.

To these four requirements, we add that an adhesive in its dry or reacted form (end state) must have the following property:

5) **elasticity**, meaning that it can stretch or deform and then return to its original state. For this to happen, it is important that polymer chains be entangled or partially connected to each other.

If all five of these phenomena (flow, penetrate, wet, set, and elasticity/ entanglement) occur, then there is likely a good match between the adhesive and the surface, and bonding should be expected. It is important to think about not only a “good adhesive”, but a “good surface” to go with it. We explore the “flow, penetrate, wet, set, elasticity/entanglement” rule as we go through our activities. We also think about the concepts of **cohesion** (when a material likes to stick to itself) and **adhesion** (when a material likes to stick to another material). Both of these phenomena are related to a material being able to wet a surface.

2. Safety

To instill good laboratory safety behavior, students should be provided with safety glasses or goggles, and must be advised against tasting any provided materials or eating while conducting the activities described herein.

3. Recording Data

While data recording for activities in this program is not required and can be omitted for younger students, older students should be encouraged to record data and observations as they work through the program if time permits. If possible, students should keep a lab notebook to record their results. If this is to be done, having a small dedicated composition book is advised. Composition books are inexpensive and usually thread-bound, reducing the risk of lost pages. Students using lab notebooks should be instructed to number pages in the book and use the first page for a table of contents. A nice summary for student notebook setup and usage is given by Causey (2020).

4. Materials

For our program and this report, we used materials that we had on hand. We recommend that our readers do the same. While we do offer suggestions for activities that involve purchase of some modestly priced equipment (most of which can be used for other activities), we primarily offer suggestions for activities that can be performed with materials available in most homes.

The adhesives that we used were Elmer's Glue-All (Elmer's or generic school glue works just fine) and Loctite Stik'n Seal (a rubber-based adhesive). The tapes we used were Scotch tape, electrical tape, Duck-brand duct tape, and Gorilla-brand duct tape. We also used aluminum foil, cling wrap, Ziploc bags, parchment paper, printer paper, a crayon or birthday candle, a marble or small rubber ball, a drinking straw, and a can of soda.

Items that we purchased for this program included a set of six "spring balances" (online for approximately $20). We also used a 1-lb steel bearing that was part of a "Smashing Spheres" set from a previous program (online for approximate $30). (By the way, students and adults alike love the "Smashing Spheres" activity.) These purchased items are not required for the activities, but will enhance the experience for students if they can be made available. We offer suggestions for alternate items that are generally readily available and inexpensive.

5. Hands-on Program

We now present eight hands-on activities related to adhesives. The program can be used in its entirety as part of a single program (time required 1.5–2 h), as part of an ongoing program (e.g., one session per week for 8 weeks), or an *a la carte* mix of activities that best suits the need for a given curriculum. We tried to offer a broad range of activities that highlight important chemistry and properties of adhesives, while at the same time offering engaging activities that give students the opportunity to work with materials and methods similar to those used by professional chemists, and make observations and conclusions about the materials being investigated.

5.1 Activity #1: Using Paper Chromatography to Demonstrate Cohesion and Adhesion

Paper chromatography is a very simple activity and a very good way to demonstrate the concepts of **cohesion** and **adhesion in a small molecule**. A more detailed discussion of paper chromatography and the concept of hydrogen bonding is given in Pesce-Rodriguez and Rodriguez (2020b).

We start with a description of the activity itself, which is fairly simple. For the example shown in Fig. 1, we cut a short strip (approximately 4 inches × 1 inch) of white paper towel. We cut two small slits near the top of the strip and inserted a plastic drinking straw into it. A pencil, craft stick, or chopstick could also be used. We used a fountain pen to make a mark near the bottom of the strip, but any nonpermanent marker (with water soluble ink) would also work well. We then suspended the strip in a recycled jelly jar containing a small amount of water. For classroom use, plastic tumblers would be a better choice than glass.

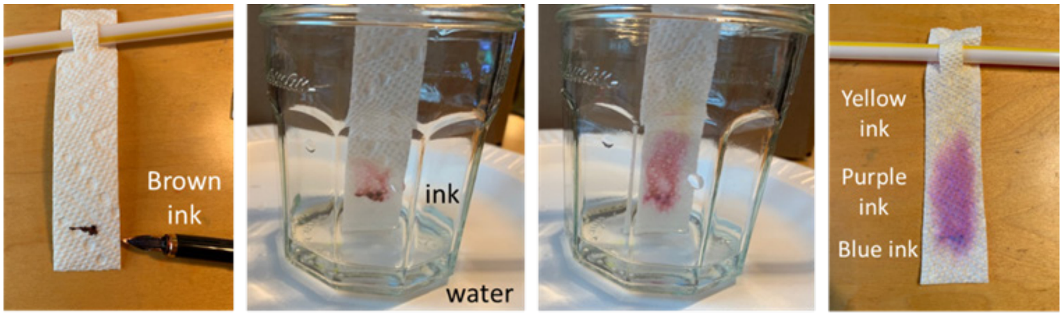


Fig. 1 Photographs of the paper chromatography activity with a brown ink. Left to right: dry paper towel strip with ink mark; paper strip suspended in jar containing a small amount of water (water is rising up the strip carrying ink with it); same, after approximately 10 s; and the strip after removal from the jar (ink colors separated into three components).

Initially, the water is on the bottom of the jar and is held together by cohesive forces. To explain to children, we can say that **cohesion is when a material sticks to itself**. As soon as the paper towel strip touches the water, the water will be absorbed and begin to travel up the paper towel strip. This interaction is an example of adhesion. Again, to explain to children, we can say that **adhesion is when a material likes to stick to another material**. As the water and paper towel interact, the water is drawn upward by adhesive forces and the components of the ink "go for a ride" with the water and separate into component colors. For the example given here, we see a dark blue ink at the point where the ink was initially deposited, then a long streak of purple ink in the middle areas of the strip, and finally toward the top of the strip a streak of yellowish ink is observed. It is recommended that instructors try this activity themselves before trying with students. Some inks work better than others. We find that students are most impressed when an ink separates into distinct colors. Crayola Changeables color change markers are particularly good for this activity because the ink in each marker is composed of two distinct colors.

In the example shown, we can say that compared with the yellow color, the purple color was more strongly attracted (i.e., had stronger adhesive forces) to the paper than the water (or else it would have continued traveling up the paper as the yellow color did).

Students can be challenged to think about (or test) interaction of water with other materials, for example, a piece of plastic bag or aluminum foil. Do they expect strong adhesive forces between water and those materials?

5.2 Activity #2: Wettability, Contact Angle, and Surface Energy

For an adhesive to be effective in bonding two surfaces, it needs to be able to first **wet** the surfaces. This means that if a drop of a material is applied to a substrate, it will tend to spread out and be attracted to the surface, versus remaining as a bead and being attracted to itself. By observing the “contact angle" that the drop makes with the surface, we can estimate how well the material wets the surface of a substrate (Fig. 2). Materials that are difficult to wet and that have high contact angles generally have low “surface energy” and a high degree of crystallinity. For polymers, being crystalline means they have a very ordered structure. As simple way to think about this is by contrasting how a dry spaghetti can pack together very tightly (“crystalline”), while cooked spaghetti is very randomly arranged (“amorphous” or “non-crystalline”). As we see in Fig. 2, materials like polyethylene (in cling wrap and Ziploc bags) and wax (from a candle or crayon) have low surface energies and high degree of order and are therefore difficult to wet with water and also difficult to bond with adhesives. (A silicone non-stick spatula would also be fun to try.) Paper and wood have high surface energies and disordered, porous surfaces and are easy to wet with water and easy to bond with adhesives.

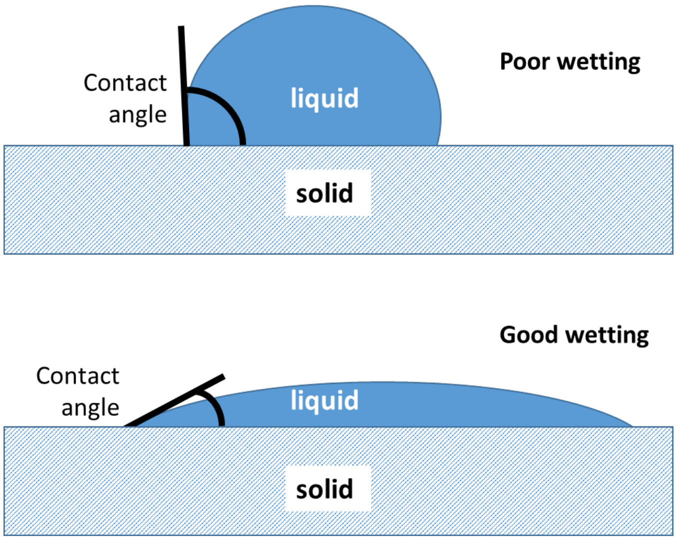


Fig. 2 Illustration showing large and small wetting angles

There are several ways to deposit drops of water on a substrate. In a laboratory, we would most likely use a disposable pipette (Fig. 3, left), but at home, a drinking straw works just fine. Shown in Fig. 3 (center and right) is the use of a straw from a juice box for transferring water (the flexible part of the straw has been cut off). By dipping the straw into a jar or cup of water and then placing a finger on the top opening of the straw, water can be held in the straw. By squeezing the straw or slightly lifting the finger covering the straw opening, drops of water can be released from the straw.

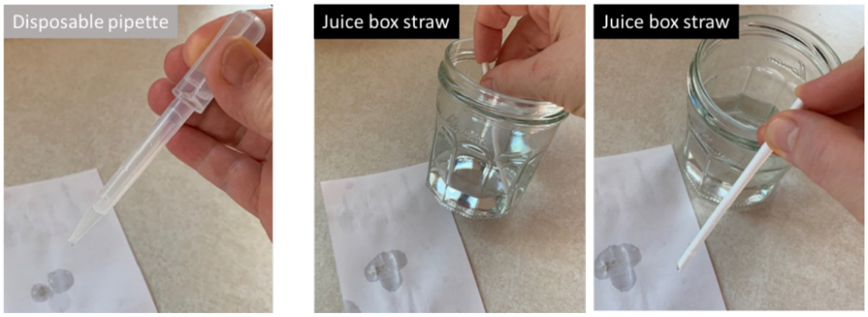


Fig. 3 Use of a disposable pipette and juice box straw to deposit drops of water on a piece of paper

In the examples shown in Figs. 4 and 5, we see that it is very difficult for water to wet parchment paper, polyethylene (from a Ziploc bag), and wax "scribbling" on printer paper. All of these surfaces repel water and can be described as "hydrophobic" (from Greek, literally, "water fearing"). Water is a polar molecule (meaning that the hydrogen and oxygen atoms that make it up do not share their electrons evenly). The result of this unequal sharing is polarity in water molecules, which is demonstrated simplistically by the magnetic water molecule models shown in Fig. 6. Water likes to stick to itself (strong cohesion), but does not like to stick to surfaces that are not polar, like the silicone coating on parchment paper, or wax. Water was observed to spread slightly on aluminum foil, which has a thin oxide surface coating, and is attractive to water. Water is absorbed by paper (as we saw in Activity #1). The reason for this is that the cellulose fibers that make up paper towel and printer paper are rich in oxygen and therefore have a polar character. Paper is also very porous and allows adhesive to seep into it. For these reasons, water likes to interact with paper or wood (strong adhesive forces). Figure 7 illustrates cohesion and adhesion of water.

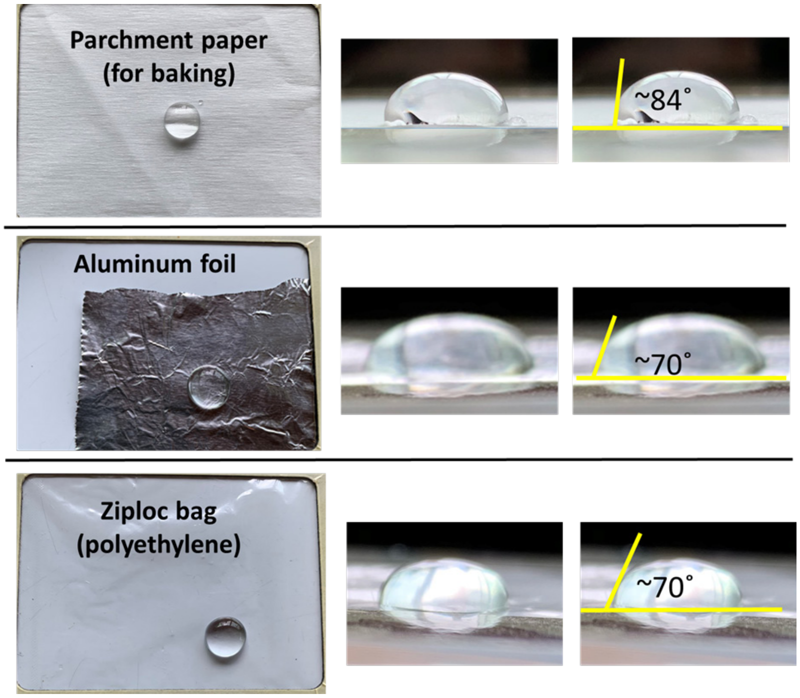


Fig. 4 Photos of drops of water on parchment paper, aluminum foil, and polyethylene (from a Ziploc bag). Photos on right show contact angles for the drops. Foils and plastics were held flat by placing a "refrigerator magnet photo frame" on them.

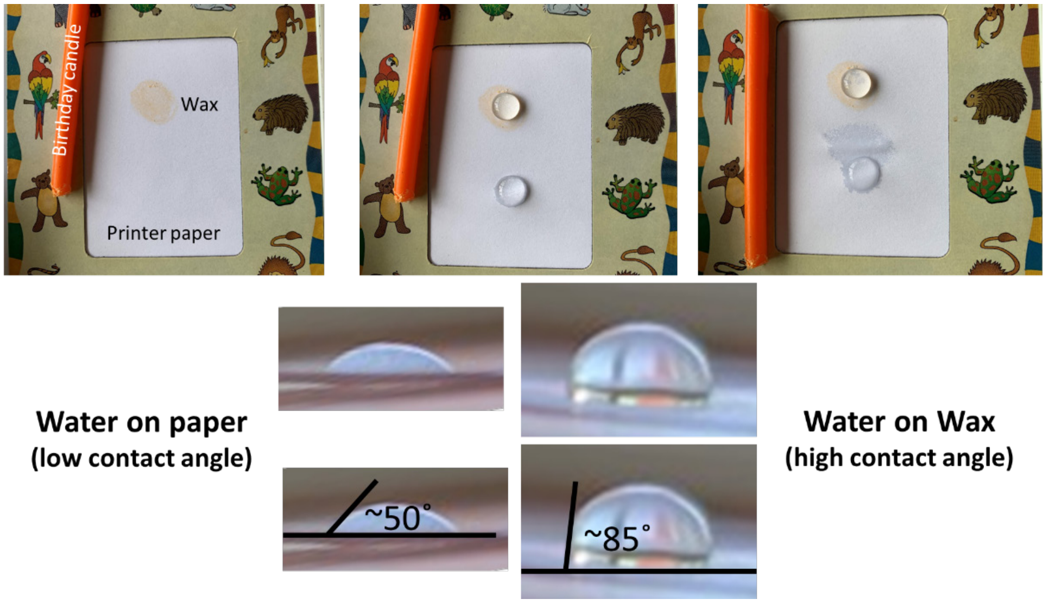


Fig. 5 Photos of drops of water on printer paper and on wax from a birthday candle scribbled on the paper. Photos at bottom show contact angles for the drops. Foils and plastics were held flat by placing a "refrigerator magnet photo frame" on them.

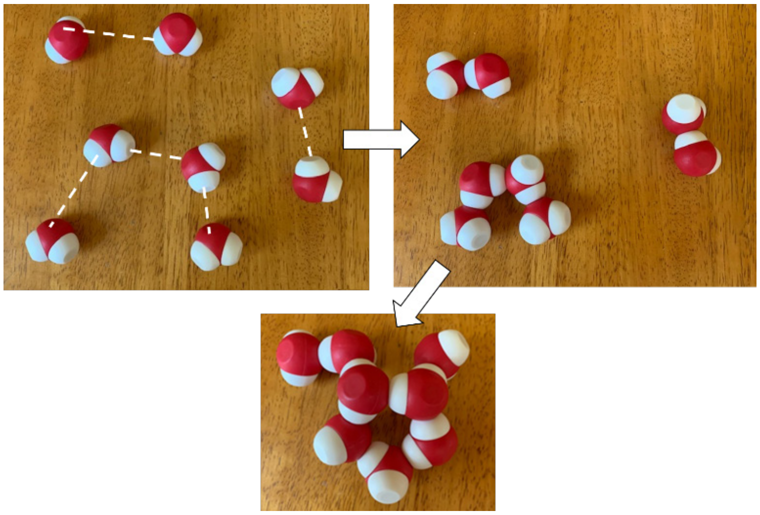


Fig. 6 **Photo of magnetic water models showing hydrogen bonding that attracts water molecules to each other (red = oxygen, white = hydrogen)**

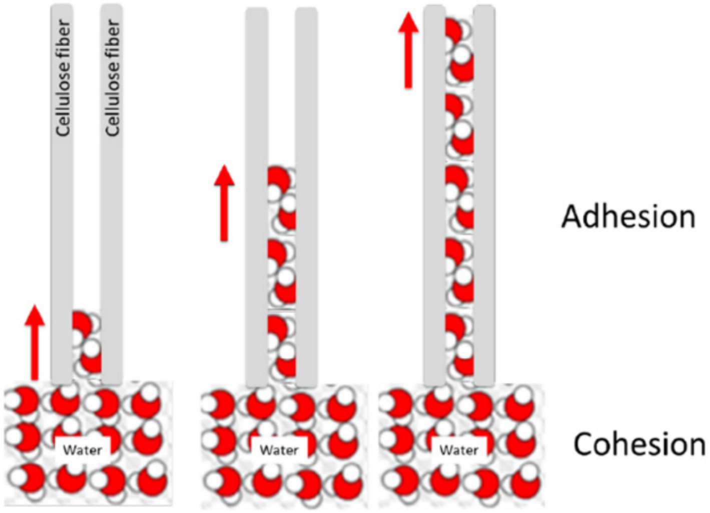


Fig. 7 **Illustration showing water attracted to itself (cohesion) and water attracted to cellulose fiber, as in paper towels (adhesion), because of hydrogen bonding**

Olive oil is made up of molecules that have both polar and nonpolar character, and tends to flow on all of the surfaces, as shown in Fig. 8. This behavior is at least partly related to the smaller cohesive forces in olive oil (that it, it is not strongly attracted to itself). The consequence of these phenomena is that the contact angles for olive oil are observed to be generally smaller than those for water.

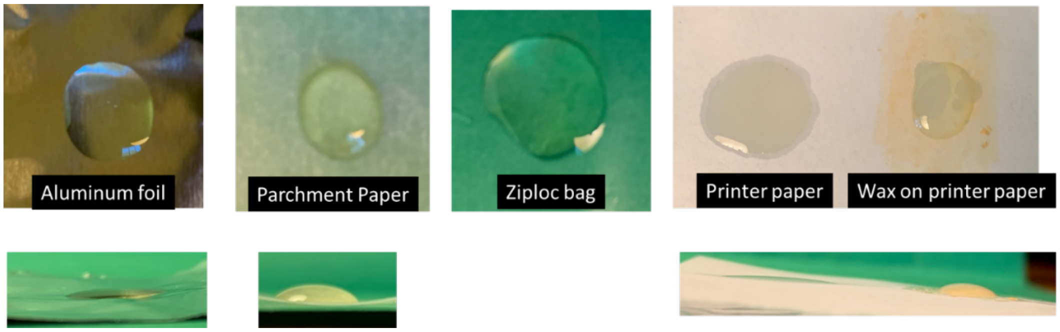


Fig. 8 Photos of drops of olive oil on aluminum foil, parchment paper, polyethylene from a Ziploc bag, printer paper, and printer paper with wax “scribbling”. Photos at the bottom show the side view for some of the drops. All have low contact angles.

5.3 Activity #3: Microscopic Analysis to Examine Diffusion into Substrates

For this module, it is essential that students have access to microscopes. While the need for microscopes for lab work may have been prohibitive in the past, several newer inexpensive microscopes have made them much more accessible. A model that we have been using for the past few years (i.e., Carson MicroBrite Plus; Fig. 9) is very popular with students and parents alike, and is available for about $13 each. The mini microscopes are fairly robust, operate with a single AA battery, and are illuminated with an LED bulb. Magnification goes to 120× and is acceptable for analysis of many different types of materials by students.

Fig. 9 Mini microscope used for observation of ink/substrate specimens

The goal of this activity is to gage the level of penetration of adhesive that might be possible based on the tendency of several surfaces to absorb ink from a permanent marker. The micrographs shown in Fig. 10 were taken using a cellphone camera through the eyepiece of the microscope in Fig. 9. The surface of parchment paper is coated with silicone and is designed to be "non-stick". It repels the ink, leaving only dry bits of ink after the solvent has evaporated. While the ink appears to adhere well to the aluminum foil, Ziploc bag, and plastic cling wrap, diffusion or penetration into the substrate is observed only for the printer paper. This occurs due to the fibrous nature of the paper. When coated with wax "scribbling", the ink can no longer diffuse into the paper and remains at the surface of the wax.

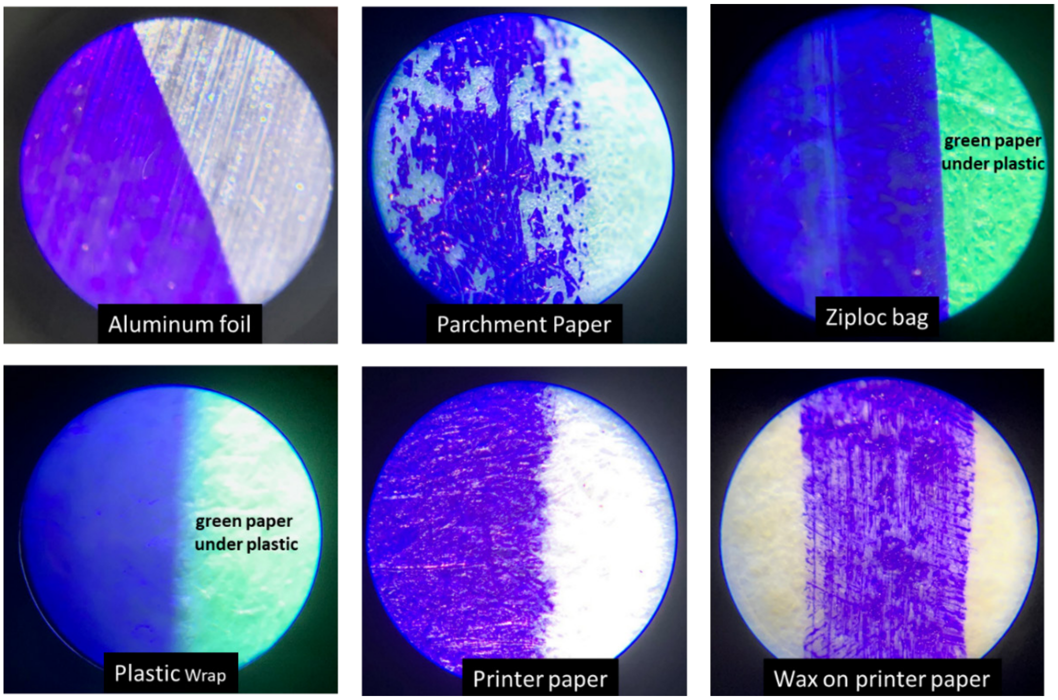


Fig. 10 Micrographs (60×) of permanent marker on various substrates. The Ziploc bag (polyethylene) and plastic cling wrap are transparent and had a piece of green paper behind them.

Let's think now about how an adhesive might interact with parchment paper and with printer paper. On which surface would an adhesive tend to flow? Into which one would the adhesive permeate or diffuse? Which would be easier to stick together with an adhesive, two pieces of parchment paper, or two pieces of printer paper? Most students know how adhesive/glue interacts with printer paper. We look at adhesion to parchment paper and some other materials in Activity #4.

5.4 Activity #4: Adhesive versus Cohesive Failure

Shown in Figs. 11–14 are photos of aluminum foil, parchment paper, cling wrap, a Ziploc bag, and craft sticks before and after failure testing. For each material tested, we applied a dab of adhesive and allowed it to dry overnight. We tested a rubber-based adhesive (Loctite Stik'n Seal) (Fig. 11) and Elmer's Glue-All (Fig. 12). We found that the rubber-based adhesive failed adhesively (that is, it failed to adhere) for the parchment paper, plastic wrap, and Ziploc bag. In each case, the adhesion to the substrate was so weak that we were able to peel off the dried adhesive as a film, indicating that it had failed adhesively (i.e., sticking to itself, rather than the substrate). The aluminum foil had a very different response: when we tried to pull apart the two foil surfaces, the aluminum tore and we observed adhesive on both sides of the torn foil, indicating that the adhesive had failed cohesively (i.e., sticking more strongly to the foil rather than to itself).

When applied to the same substrates, Elmer's Glue-All (Fig. 12) failed adhesively for only the parchment paper, the only substrate that allowed the glue to fully dry. When the foil, cling wrap, and Ziploc specimens were peeled apart, we observed that the glue was still a bit wet and would stick to our fingers if touched. We can describe the glue as being "tacky". When trapped between two sheets of aluminum, or polyethylene, the water-based Elmer's Glue-All apparently needs longer to dry than does the alcohol-based Stik'n Seal (rubber-based) adhesive. When allowed to dry completely in open air, it was possible to remove the dried Elmer's Glue-All as a film. No tackiness was observed (Fig. 13). Despite the name, Elmer's Glue-All (like the rubber-based Loctite Stik'n Seal) is not a good adhesive for "all" materials, especially those with low surface energies (like cling wrap, a Ziploc bag, and parchment paper).

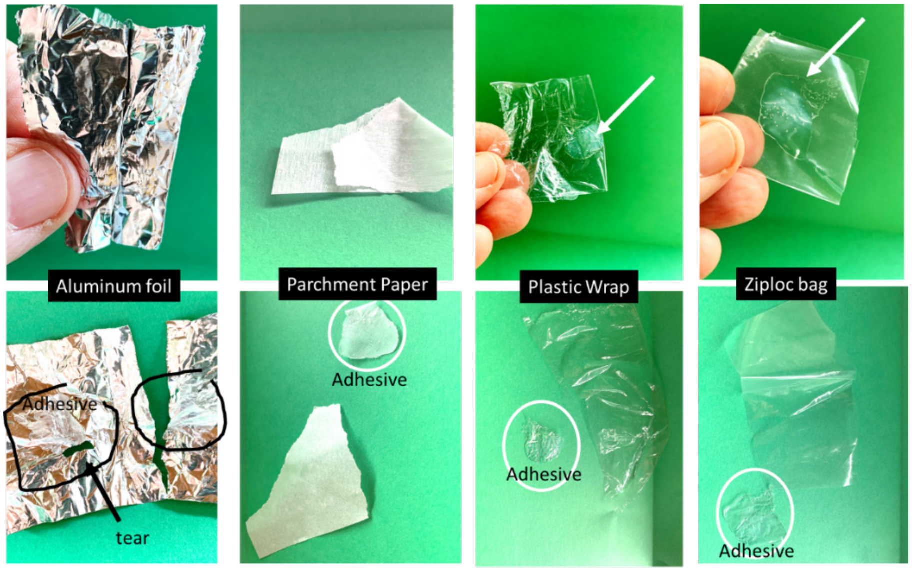


Fig. 11 Photos of a rubber-based adhesive (Loctite Stik'n Seal) on aluminum foil, parchment paper, and polyethylene from cling wrap a Ziploc bag. Top: as-prepared specimens. Bottom: specimens after peeling back substrate surface. The adhesive was easily recovered as a film from the parchment paper, cling wrap, and Ziploc bag specimens, indicating adhesive failure ("failed to adhere to substrate"). The rubber adhesive on the aluminum foil demonstrated cohesive failure (adhesive failed to stick to itself).

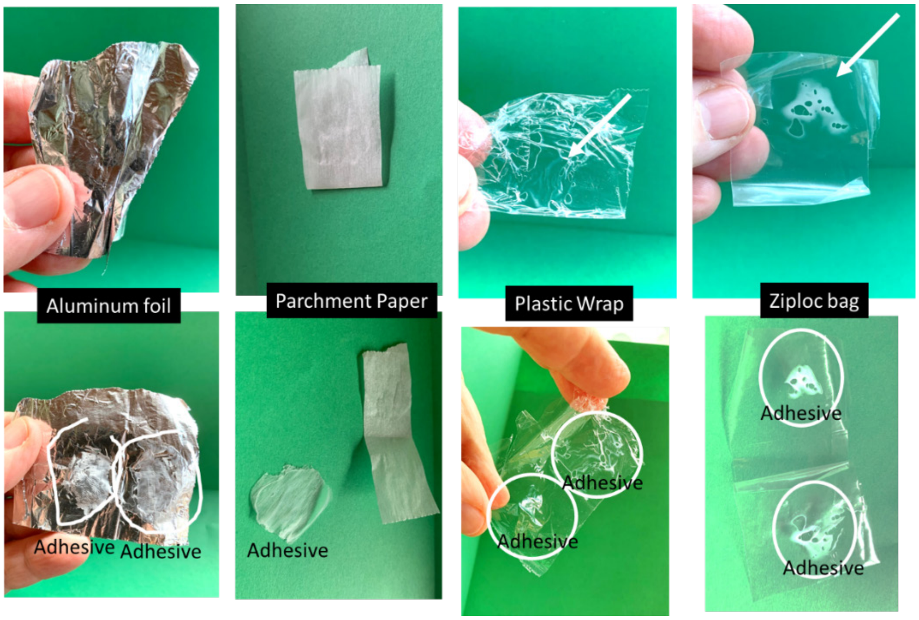


Fig. 12 Photos of Elmer's Glue-All (not yet completely dry) on aluminum foil, parchment paper, and polyethylene from cling wrap and a Ziploc bag. Top: as-prepared specimens. Bottom: specimens after peeling back substrate surface. The adhesive was easily recovered as a film from the parchment paper, indicating adhesive failure. The adhesive on the aluminum foil, cling wrap, and Ziploc bag specimens appears to demonstrate cohesive failure (the adhesive "failed to stick to itself").

Fig. 13 **Photos of Elmer's Glue-All (completely dry) on polyethylene from cling wrap and a Ziploc bag. The dry adhesive was easily recovered as a film from the cling wrap and Ziploc bag specimens demonstrating adhesive failure ("failed to adhere to substrate").**

When applied to wooden craft sticks ("Popsicle sticks"), both the rubber-based adhesive and the Elmer's Glue-All failed cohesively (Fig. 14) when we pressed our fingers between the sticks. (A pencil or pen could also be used.) This means that the bond formed between the adhesives and the wood was stronger than the bond of the wood fibers to themselves and is exactly what we want to happen when we glue surfaces together.

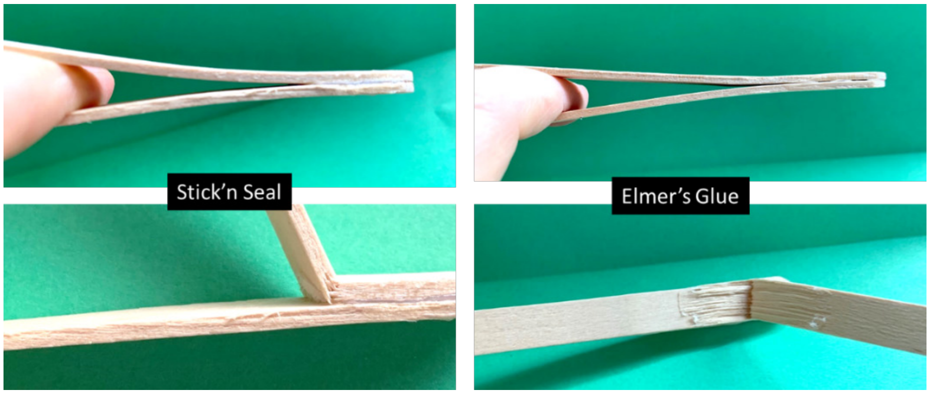


Fig. 14 **Photos of glued wood when pried apart. In both cases, the bond was stronger than the wood itself**

5.5 Activity #5: Roll Test to Determine Adhesive Strength

In this test, we determine the relative adhesive strength of several common tapes. Each tape has a plastic film on one side and a sticky "pressure sensitive adhesive" (PSA) on the other. To prepare the test apparatus (Fig. 15), we first fixed a piece of tape sticky-side up to the back of a plastic tray (a piece of cardboard, a clipboard, or other stiff surface can be used instead). We then propped up the tray on a box of pasta (a stack of books or a couple of soup cans could be used instead). We measured the incline with a cellphone app (it can be found under a utilities/measure/level or under the measure app, depending on the phone). We then used a steel sphere that we had on hand from another science, technology, engineering, and mathematics (STEM) activity to measure the stickiness of each tape based on the time it took for the sphere to roll down the incline. As shown in Fig. 16, Scotch tape, electrical tape, and clear packing tape were not very sticky; the ball rolled down immediately. The Duck and Gorilla tapes were very sticky and the steel sphere took a long time to roll down the incline. For less sticky tapes (like Scotch, electrical, and packing tapes), it would have been better to use a marble or small rubber ball to measure roll time. If using a ball that was so light, we would have waited a very long time indeed for it to roll down the Duck and Gorilla tapes.

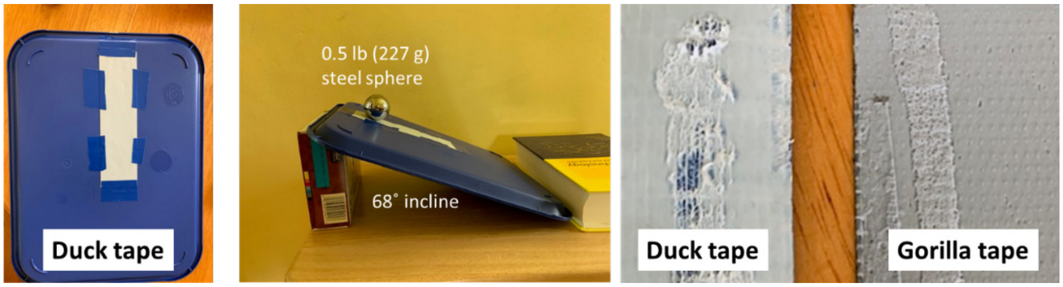


Fig. 15 Photos of the "roll test" setup (left, center) and the Duck and Gorilla tapes after testing (right)

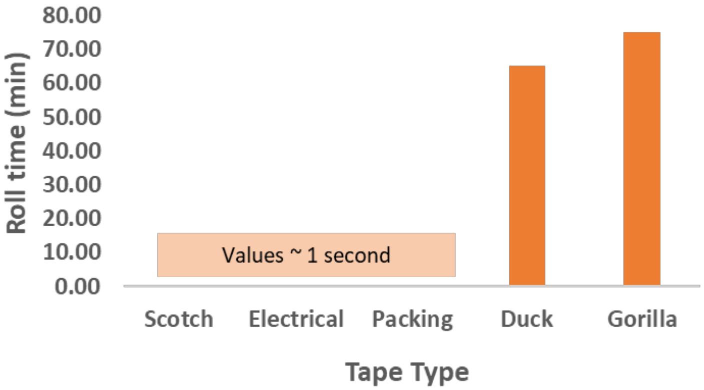


Fig. 16 Results of the "roll test" on five tape samples

An alternative way to conduct this "roll test" is described in "Celebrating Chemistry: Sticking with Chemistry." (https://www.acs.org/content/acs/en/education/outreach/celebrating-chemistry-editions.html)

Examination of the "tracks" left after the steel sphere had rolled down the strips of Duck and Gorilla tape (Fig. 15, center and right, respectively) shows that the Gorilla tape was more resilient than the Duck tape, which pulled away from the tape, revealing the blue plastic film on the outer layer. As shown in Fig. 17, when the sticky side of the Duck or Gorilla tape is stuck to itself and then pulled apart, we can observe the elastic or stretchy character of the adhesive. This stretchiness is important for adhesives. If the material cannot stretch and then return to its original state (like a rubber band does when stretched and then released), then material would be considered to be brittle and would not make a good adhesive.

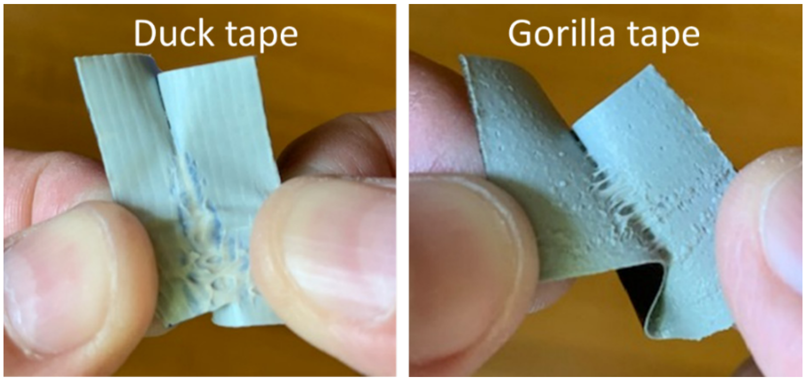
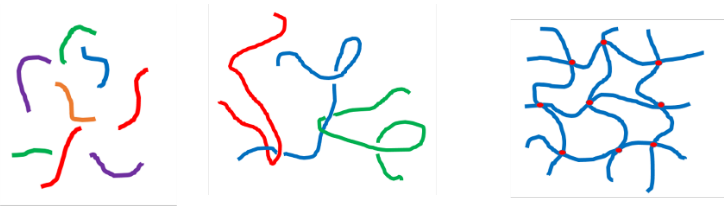


Fig. 17 Photos of two sticky surfaces of Duck and Gorilla tapes stuck together being pulled apart. Note the elastic quality of both adhesives.

To understand how polymers can be elastic, we need to remember two things: the polymer should have carbon (C=C) bonds in its "backbone" (bonds hanging off the chain do not count) and, like in the Goldilocks story, the chain length has to be "just right". If the chains are too short, they cannot entangle and be pulled back after being stretched. If they are too crystalline (like polyethylene in a Ziploc bag) or too long (usually this means "highly cross linked", or chemically linked to each other), then they are not be able to stretch much in the first place, but might still make a good adhesive if they can stretch a bit and absorb energy When a polymer chain length (chemists will talk about "molecular weight") is just right, then chains can entangle; when they are stretched, they can relax back to more or less to their original position. Figure 18 shows this graphically.



Short chains
can't entangle
can't be elastic

Long chains
easy to entangle
can be elastic

Long, cross-linked chains
fixed in place
can't be elastic

Fig. 18 Illustration showing how chain length and cross-linking can affect elasticity. The chain length has to be just right to allow entanglements.

Given that most homes and schools do not have a heavy steel ball on hand for this test, an alternate would be an unopened soda or soup can (paper label removed). A photo of this test is shown in Fig. 19. Unlike the steel sphere, which contacts the tape in a very small area, a can contacts across the full width of the tape. To be sure that conditions for testing are a similar as possible for all tape types (i.e., narrow electrical tape or scotch tape versus wide duct tape), the tape can be cut and tested in thin strips of equivalent widths (as shown in Fig. 19, right, for Gorilla tape).

Fig. 19 **Setup for the "roll test" using a thin strip of tape and a soda can roller**

5.6 Activity #6: Peel Test to Determine Adhesive Strength (Semiquantitative)

While we prefer to use commonly available materials in our STEM activities, we also recognize the value of making measurements that are more quantitative than those made in the "roll test" with a steel sphere or can of soda or soup (Activity #5). We therefore offer our readers an inexpensive yet semi-quantitative alternative to measuring differences in "peel strength" of various tapes. The technique involved using "spring balances". We purchased the set in Fig. 20 online for approximately $20. The set can measure masses ranging from 0 to 500 g and forces from 0 to 50 newtons (N). Each of the different spring balances measures a different range, as indicated in Fig. 20.

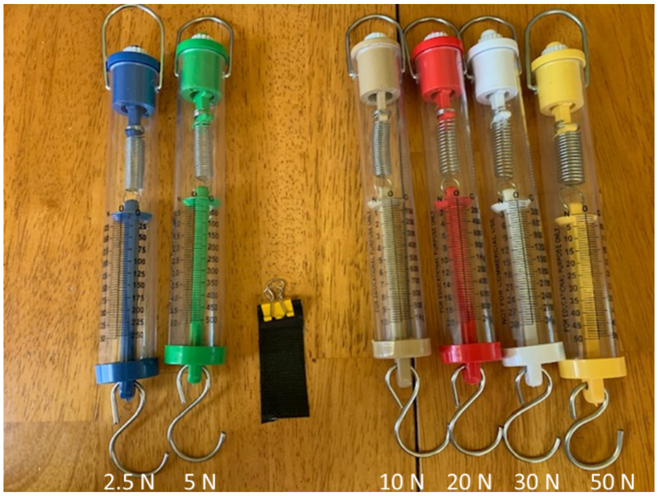


Fig. 20 **Set of spring balances used to measure the peel strength of adhesive tape samples. The maximum force that can be measured is given in the labels on the bottom of the photo.**

We used the spring balances to measure the peel strength of four tape samples: Scotch tape, electrical tape, Duck tape, and Gorilla tape. For each tape, we first folded one end of the strip to thicken it and then fixed a small binder clip to it. We then hooked the spring balance into the binder clip and pulled up on the spring balance to see if we could peel the tape from the table. We started with the spring balance with the lowest range (the blue one in our set). As shown in Fig. 21, at full range for the blue balance (2.5 N) and green balance (5.0 N), we were unable to peel the Gorilla tape. When using the beige balance, we found that we could peel the tape at 7.0 N. The force remained at that value throughout the peel. We then used the same process to measure the peel strength of the other tape specimens and plotted the results in Fig. 22. The adhesive for the Gorilla tape was found to be the strongest, while that for the Scotch tape was found to be the weakest.

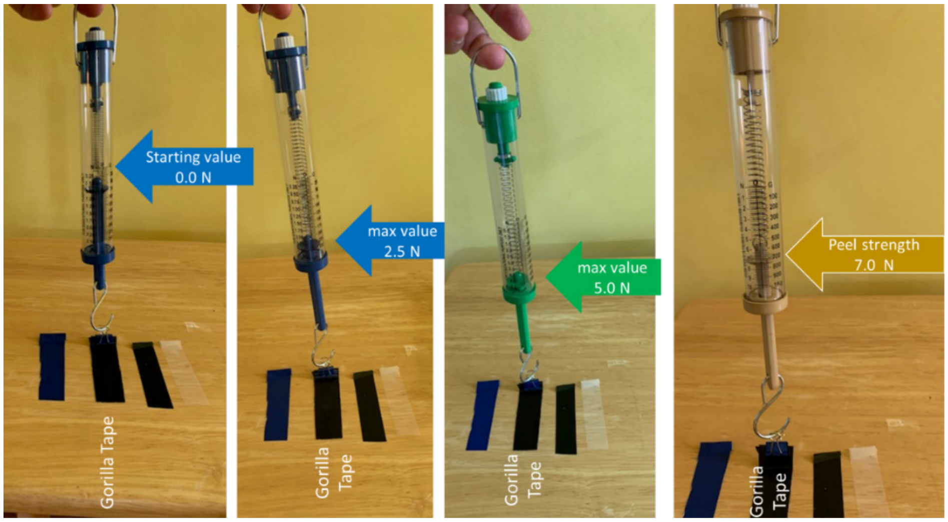


Fig. 21 Photos showing sequence of testing with three spring balances before finding the balance with the correct force range

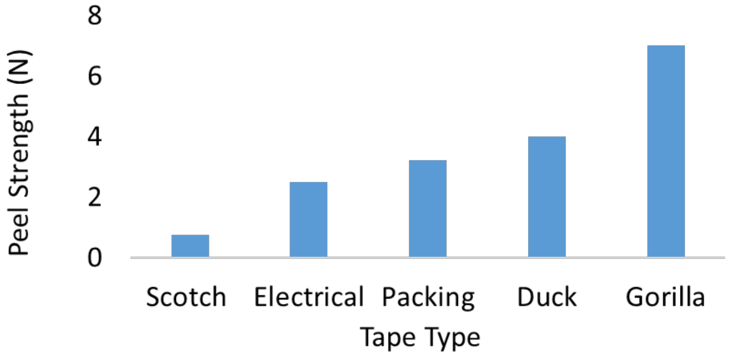


Fig. 22 Results of the "peel test" on five tape samples

5.7 Activity #7: Making Glue

As noted in the introduction, humans depended on natural materials for adhesives up until the 1940s and World War II. While natural adhesives suffer from the disadvantage of being biodegradable and are therefore not appropriate for many applications, there are several application for which they are well suited. For example, “hide glue” is considered to be the best adhesive for wooden musical instruments like violins and guitars, as well as for making match heads and “gummed taped” (the paper tape used to seal Amazon boxes) (Pearson 2003). Gum arabic is used for sealing envelopes that people lick to moisten (Baumann and Conner 2003). Several natural adhesives can also be made at home for craft or school projects, and can be a fun and educational activity for students. As such, we offer information on the preparation of several natural adhesives in the following sections.

5.7.1 Glue from Milk

Milk glue is sometimes called casein glue because of the protein in milk that actually forms the adhesive. To prepare it, one needs the following: milk powder, water, baking soda, and vinegar. Specific directions can be found at https://hubpages.com/art/woodworking-how-to-make-your-own-strong-wood-glue-from-milk.

To summarize the process, prepare the milk as per the instructions on the package. This can be done directly in a pan. Vinegar is then added to the milk (15 mL for 100 mL of milk). The mixture is heated gently until it curdles. After removing from the heat, the solids are collected by filtering through a coffee filter or paper towel in a funnel and then rinsed with water to remove the vinegar. Baking soda (1/2 tsp) is added to the solids and stirred with a craft stick. Water is then slowly added until a glue-like consistency is achieved.

5.7.2 Glues from Gelatin, Flour, and Milk

A description of an activity related to glue making was prepared by the ACS (2008): “From Goo to Glue”, https://www.acs.org/content/dam/acsorg/education/resources/k-8/science-activities/characteristicsofmaterials/building/from-goo-to-glue.pdf. This activity suggests a trial-and-error experimental approach to making glue with gelatin, flour, and milk. As in our activities described previously, they suggest trying the glue formulation on various substrates including aluminum foil, plastic bags, paper, craft sticks, and so on.

Another activity, described on the Beneylu School website, https://beneylu.com/pssst/en/cheap-stem-experiments/, suggests a similar approach to “inventing” new glue formulations, followed by testing the strength of the bond of dried glue to a paperclip. The test is performed by hanging metal washers on the paperclip until the bond fails.

3M gives a lesson plan and academic standards for a flour-glue activity: https://www.youngscientistlab.com/sites/default/files/lesson_plans/K2_StickTogetherFunWithAdhesives.pdf.

A basic procedure for making glue from starch (flour) is given by the easternblot.net blog, https://easternblot.net/2007/01/24/why-is-bread-not-glue/, in which 1 cup of flour is added to cold water and then that mixture is added to 3 cups of boiling water to create the glue.

5.7.3 Homemade Glues from the Past

For a fun historical perspective on the days when we could not run to a nearby store or go online for our home adhesive needs, the reader is referred to an 1898 issue of *Good Housekeeping* (Kelly 1898), which can be accessed through Google Books. That article describes methods for preparing various adhesives for many purposes including applying wall paper, adding items to scrapbooks, sticking labels to "tins" (metal cans) and glass, and sticking paper to wood. However, one formulation, "warranted to stick tight to almost anything", calls for the use of lead acetate, which is very poisonous.

5.8 Activity #8: "Glue in the Dark"—Luminescence of Adhesive Tapes

While researching background information about adhesives, we came across an interesting reference from modern times that cited a much older work. The older reference was a 1939 paper by NE Harvey who reported on the luminescence of adhesive tape. A modern reference (Camara et al. 2008) took Harvey's work a step further and showed that not only could visible light be generated when tape is peeled away from the roll, but X-rays as well! Not to worry; the latter phenomenon only occurs when the unrolling is done under vacuum. The authors actually used the X-rays they generated while unrolling Scotch tape to image one of their fingers. According to Camara et al., "*When the tape is peeled, part of the energy supplied is converted to elastic deformation of the tape, cavitation* (i.e., formation of small vapor-filled cavities or "holes" in the adhesive) *and filamentation* (i.e., growth of stringy filaments as we saw in Fig.17) *of the adhesive, acoustic emission* (i.e., the sound we hear when tape is pulled from the roll)*, visible light* (i.e., the green luminescence) *and high-energy electron emission* (i.e., the X-rays)."

We were intrigued by Harvey's work on the luminescence of tape and decided to give it a try. We took a roll of Scotch tape into a darkened room and pulled on the tape. We could not see anything. We tried again with duct tape and did see green luminescence! The key is to pull the tape hard and look in the right place (Fig. 23).

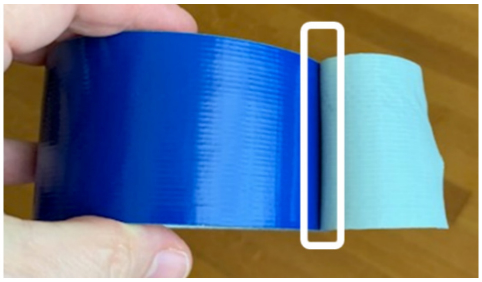


Fig. 23. Photo of a roll of duct tape showing where to look for luminescence when peeling away tape from the roll in a dark room

6. Conclusion

In preparing this report, we immersed ourselves in world of adhesives (figuratively, not literally!) to arrive at a level of understanding for our own knowledge and the sake of our program participants or any instructor or student who might be interested in learning more about the topic. We explained the complex chemistry of adhesives in simple terms that might best for teaching young students. We hope that our readers and their students will choose to follow up with additional reading and experimentation on their own to learn more about the field.

For children, we highly recommend downloading "Celebrating Chemistry: Sticking with Chemistry" (https://www.acs.org/content/acs/en/education/outreach/celebrating-chemistry-editions.html). For adults, a new book on adhesion is very informative and makes for great reading (Abbott 2020).

We found adhesives to be a very accessible topic and one that can be readily pursued "on a budget" with K–12 students. We expect that, like us, students who learn more about adhesives and the chemistry behind them will start to notice them in the world around them, and perhaps, "Stick with Chemistry!" as a hobby or profession.

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List of Symbols, Abbreviations, and Acronyms

ACS	American Chemical Society
ARL	Army Research Laboratory
CCDC	US Army Combat Capabilities Development Command
STEM	science, technology, engineering, and mathematics

1 DEFENSE TECHNICAL
(PDF) INFORMATION CTR
DTIC OCA

1 CCDC ARL
(PDF) FCDD RLD CL
TECH LIB

1 CCDC ARL
(PDF) FCDD RLW LB
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