ARL-TR-8968 ● May 2020

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

by RA Pesce-Rodriguez and A Rodriguez

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

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14. ABSTRACT

In Part III of a series of hands-on science, technology, engineering, and mathematics (STEM) programs for K–12 students and interested adults, we provide background information and specific guidance on materials and procedures for 10 activities related to paper. All activities are designed to be executable with minimum expense and hazard. Our 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 origin of paper. The program was developed as part of a 2019 “Chemists Celebrate Earth Week” program jointly sponsored by the US Army Combat Capabilities Development Command Army Research Laboratory and the American Chemical Society.

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1. Introduction and Background Information

The genesis of this program was our 2019 “Chemists Celebrate Earth Week” (CCEW) program jointly sponsored by the US Army Combat Capabilities Development Command (CCDC) Army Research Laboratory (ARL) and the American Chemical Society (ACS). Our “Chemistry in the Library” program focused on the 2019 CCEW theme: “Take Note – The Chemistry of Paper”. A dozen programs were run at public libraries in several Maryland counties.

The goal of this and every program that we run is to promote awareness of chemistry and bring hands-on chemistry to the public. We strive to make students and adults more aware about the materials that we use and rely on in our daily lives, and further to consider where those materials come from and what sustainability issues are associated with them. We seek to offer interesting, thought-provoking activities that are safe to perform in a library environment and that involve materials and equipment that are inexpensive and readily available. We encourage families to follow up on the content in our programs and often offer suggestions for how ideas in our programs can be explored as science fair projects. While our program is mainly focused on children, parents are always encouraged to attend the program (and are required to attend if children are younger than 9 years old). We also run an evening program for families and adults without children. The program was established in 2003 and has since served well in excess of 5000 children and adults.

We began our current program’s introduction with a question for students, what are some uses of paper? Here are some of the uses we came up with. Instructors and students can likely expand the list:

- Writing/ communication
  - Homework
  - Record keeping
  - Letters
  - Cards
  - Newspapers
  - Magazines
- To represent things of value
  - Money
  - Tickets
  - Checks
  - Property deeds
  - Contracts
- Packaging
  - Wrapping
  - Boxes/cartons
  - Tissue paper
  - Egg cartons
- Cleaning
  - Paper towels
  - Toilet paper
  - Tissues
- Disposables for food
  - Paper plates
  - Napkins
  - Takeout containers
- Decorations
  - Wall paper
  - Signs
  - Crepe paper
- Health care
  - Hospital gowns
  - Face masks
- Construction
  - Papier mâché
  - Paper planes
  - Origami
  - Sand paper
  - Japanese windows (Washi)
- Laboratory
  - Filter paper
  - Litmus paper
  - Paper chromatography

We next give a brief history of writing substrates and paper. Two references that we found to be particularly useful in learning about the history of paper and papermaking are Kurlansky (2016) and Hunter (1978). Here is brief list of topics that instructors might like to discuss with students:

1) Clay: Symbols and images were scratched into wet clay using a stylus (usually a stick). The clay would harden as it dried and become a lasting record. Examples of the use of clay as a writing substrate goes back as far as 9000 BCE.

2) Papyrus: Papyrus plant stems were dried and flattened and then arranged in alternating layers before being hammered together to form a single sheet. Once dried, papyrus is a substrate that can be written upon. It was used by ancient Egyptians as far back as 4000 BCE, often in the form of scrolls. Some ancient documents written on papyrus exist today, some dating back to 2500 BCE. Papyrus is not classified as a paper.

3) Parchment: Untanned animal skins were used to produce a substrate that can be written upon. It appears that Egyptians may have used parchment as far back at 2500 BCE. Many important American historic documents were written on parchment, including the Declaration of Independence, the Bill of Rights, and the Constitution. Parchment is not classified as a paper.

4) Hemp paper: Fibers collected by beating rags made from hemp (think dryer lint!) were used to make paper in China as far back as 140 BCE. Hemp fibers are 4–5 times longer than fibers from wood pulp, imparting a higher tear resistance and tensile strength. They also have a lower lignin fraction than wood, making them easier to process. Paper made from hemp can be recycled up to 7 times, whereas paper from wood fiber can be recycled only up to 3 times.

5) Mulberry paper: Fibers from the bark of mulberry trees can be beaten into fibers and used to make a tough paper. The paper is generally made by hand (even today) and produces a very strong paper that can be used not only for writing but for clothing and household goods (including semitransparent window screens and room separators in Japanese homes). Cai Lun, a Chinese inventor, is often credited with the "invention" of papermaking, but he was actually responsible for significant improvements in the papermaking process and for establishing a greatly improved paper formulation.

An example of papermaking in nature can be observed in Fig. 1, which shows the nests of the paper wasp. A Frenchman, René Antoine Ferchault de Réaumur (1683–

1757), speculated as to why humans did not make paper from wood as paper wasps did (Hunter 1978). Unfortunately, he was a naturalist, not a papermaker, and it would take another 100 years before papermakers would take up the idea of making paper from wood pulp.

Fig. 1 Photos of nests made by the paper wasp

The current process for making paper on an industrial scale is summarized in Fig. 2, which is modified from a document published by the ACS (2019). The cartoon was specifically designed for the 2019 CCEW theme in a manner that would be both appealing and informative for students. A copy of this document, as well as those on past CCEW and National Chemistry Week themes, are available at https://www.acs.org/content/acs/en/education/outreach/celebrating-chemistry-editions.html.

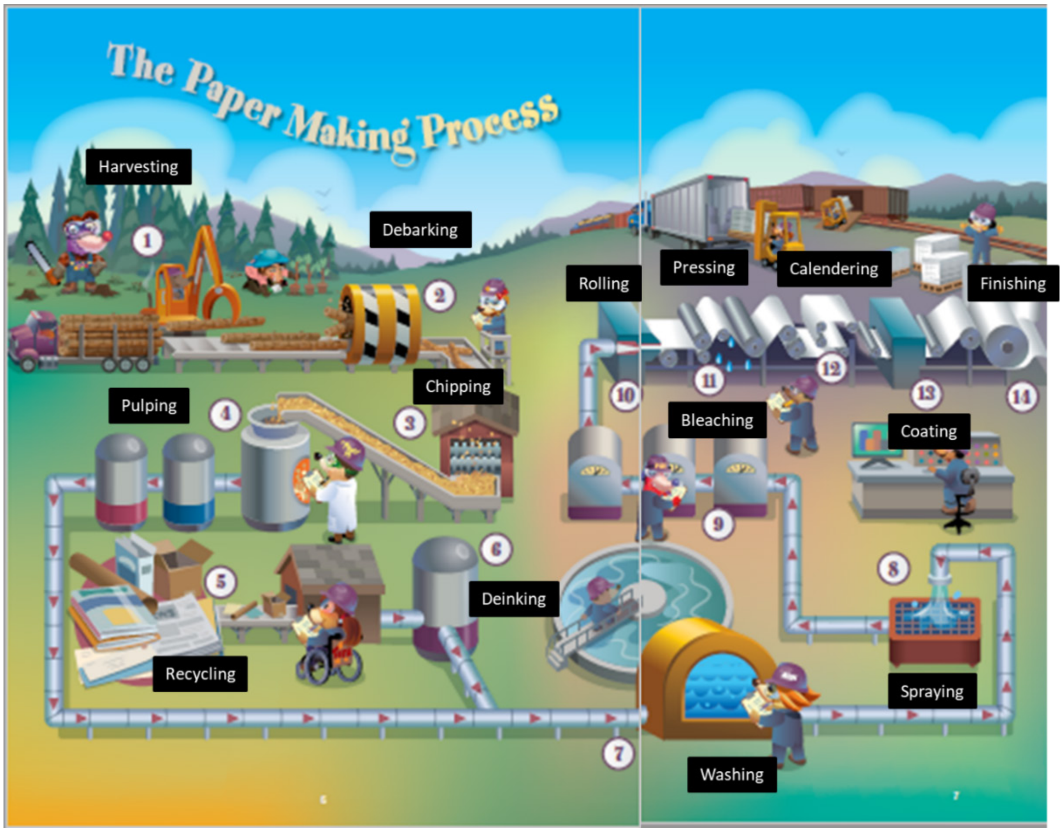


Fig. 2 **Cartoon showing the industrial papermaking process (modified from ACS [2019])**

1.1 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.

1.2 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 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 (n.d.).

1.3 Paper Samples

For this program, it is ideal to make several different types of paper available for students to examine and test. We list here the types of paper that we used along with their characteristic features. Other types of paper are also appropriate for this program. It is recommended that instructors use materials that are most readily available, especially if sticking to a low budget is important.

- Printer paper is one of the most readily available types of paper. It is characterized by a bright, white appearance that is ideal for contrasting with black ink for easy reading. Printer paper has a fibrous wood-based inner layer and a smooth nonfibrous outer layer (Fig. 3), generally made of clay, calcium carbonate, and starch. The surface coating makes the paper smooth and prevents excess absorption of ink. The calcium carbonate in the surface coating makes the paper alkaline and prevents acid hydrolysis (breakdown) of the paper, giving it a long lifetime and making it useful for archiving information.

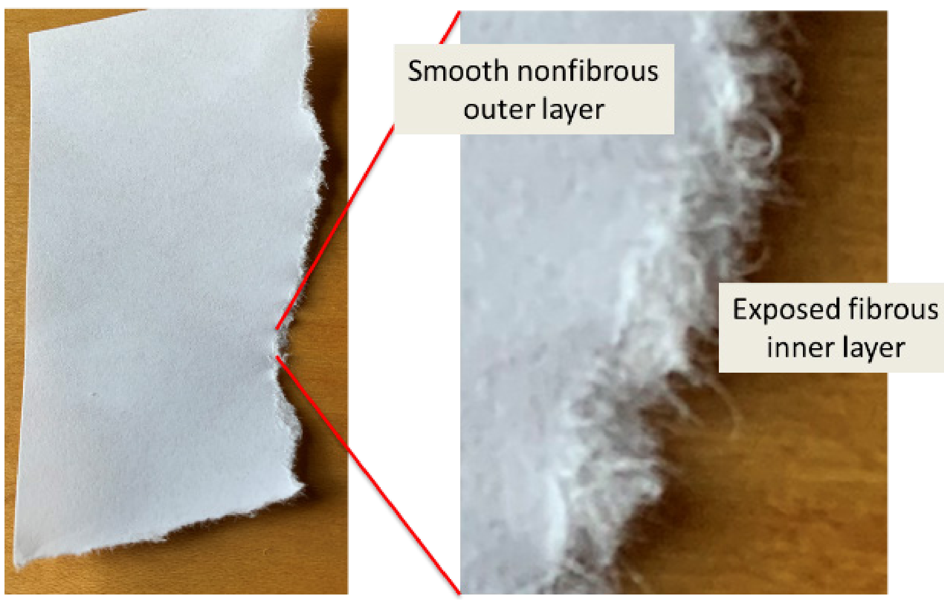


Fig. 3 Photo of the torn edge of printer paper showing the smooth outer layer and fibrous inner layer

- Paper towel is made of wood-based fibrous material similar to that of the inside layer of printer paper, but it has no surface coating. Unlike printer paper, absorption of ink or other water-based liquids is highly desirable, making surface coating unnecessary. Paper towels are disposable and not intended to have a long lifetime, so do not need to be stabilized with calcium carbonate.

- Brown paper from supermarket or lunch bags, or cardboard from boxes, is generally made of unbleached wood-based fibrous material with no surface coating. The job of brown paper and cardboard is to serve as a packaging material. Its main requirement is strength. While brown paper from bags and boxes does not need to be colored, it often is for specific purposes. When it is coated with some kind of ink, the surface is coated in a manner similar to that of printer paper.

- Mulberry paper can be purchased online, but can be replaced by homemade paper. Given that one of the activities in this program is the making of homemade paper, instructors who practice that activity before running the others with students will likely have ample material on hand for students to test.

- As already discussed, papyrus is not paper, but is interesting for students to observe and test, especially with respect to observing differences between papyrus and paper. Because the fibers in papyrus are never broken down to make the product, loose fibers will not be observed if viewed under a microscope.

- Hemp paper can be purchased online, but is also readily available (as rolling paper) in tobacco shops. Hemp paper can be either bleached (white paper as used for most cigarettes) or unbleached. The paper is very fine yet strong. Hemp fibers from clothing or twine can also be examined, but are not suitable if the goal is to compare various paper types.

- Paper with a watermark is often as close as a student's last report card. Watermarks can also be found on passports, US currency (Fig. 4), and other official documents. Watermarked papers is examined for their watermarks only and not consumed in analyses.

Fig. 4 Backlit photo of $10 bill with the watermark image of Alexander Hamilton

2. Activity #1: Microscopy

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 are currently available online. A model that we have been using for the past few years (i.e., Carson MicroBrite Plus; Fig. 5) is very popular with students and parents alike, and is available for about $10 each. The 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 paper analysis by students. Mini microscopes with magnifications of up to 250× are available from the same vendor, but we find them difficult for younger students to work with and recommend the lower magnification model because it provides a wider view of the sample.

Fig. 5 Mini microscope used for observation of paper specimens

For this activity, we started with two materials that are not papers so that we could emphasize the differences between paper, which is a felted product, and woven materials. Shown in Fig. 6 are the all the specimens we examined, including pieces of felt and an old woven dishcloth. Figure 7 shows microscopic images of the felt and dishcloth taken with a cellphone camera through the view of the microscope in Fig. 4. While the old dish towel has many “stray” fibers, it is mostly well organized, while the felt is a disordered mass of fibers. It is the lack of organization of fibers in felt which is most similar to that of paper.

Fig. 6 Photo of felted and woven specimens (papyrus, papers, felt, and a scrap of old dish towel)

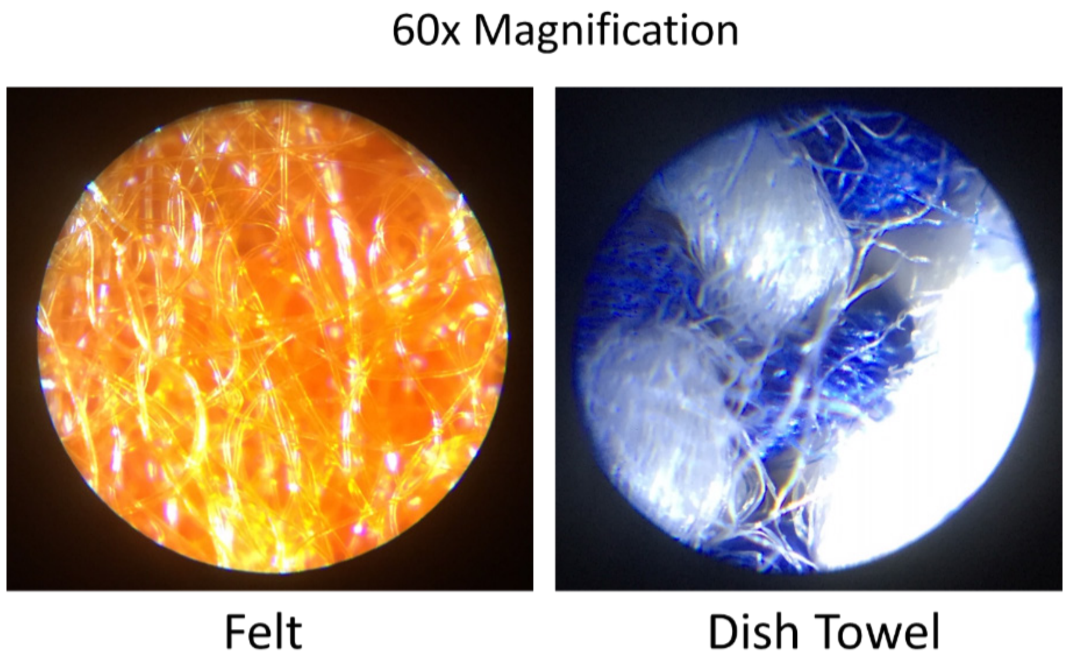


Fig. 7 Micrographs of the felt and a scrap of old dish towel. While there are some stray fibers in the old dish towel, most fibers are well ordered, while the fibers in felt are completely disordered.

Shown in Fig. 8 are micrographs of papyrus and the five paper specimens shown in Fig. 6. Each specimen had been labeled with a fine-point marker. Examination of how ink interacts with the paper is an interesting exercise for students. Observations that can be made include the following:

- Presence of fibers
    - Papyrus has no visible fibers.
    - The fibers in printer paper are difficult to observe.
    - Fibers are obvious in paper towels and brown, hemp, and mulberry papers.
- Thickness of fibers
    - The fibers in hemp paper are very thin.
    - The fibers in brown and mulberry paper are very thick.
- Loose fibers
    - The paper towel has very loose (noncompacted) fibers.

- Bleed/sharpness of lines
  - Paper towel absorbs the ink very well.
  - Papyrus and hemp paper absorb the ink very poorly.
  - Brown and mulberry paper absorb the ink moderately well.
  - Printer paper has a very sharp ink lines.

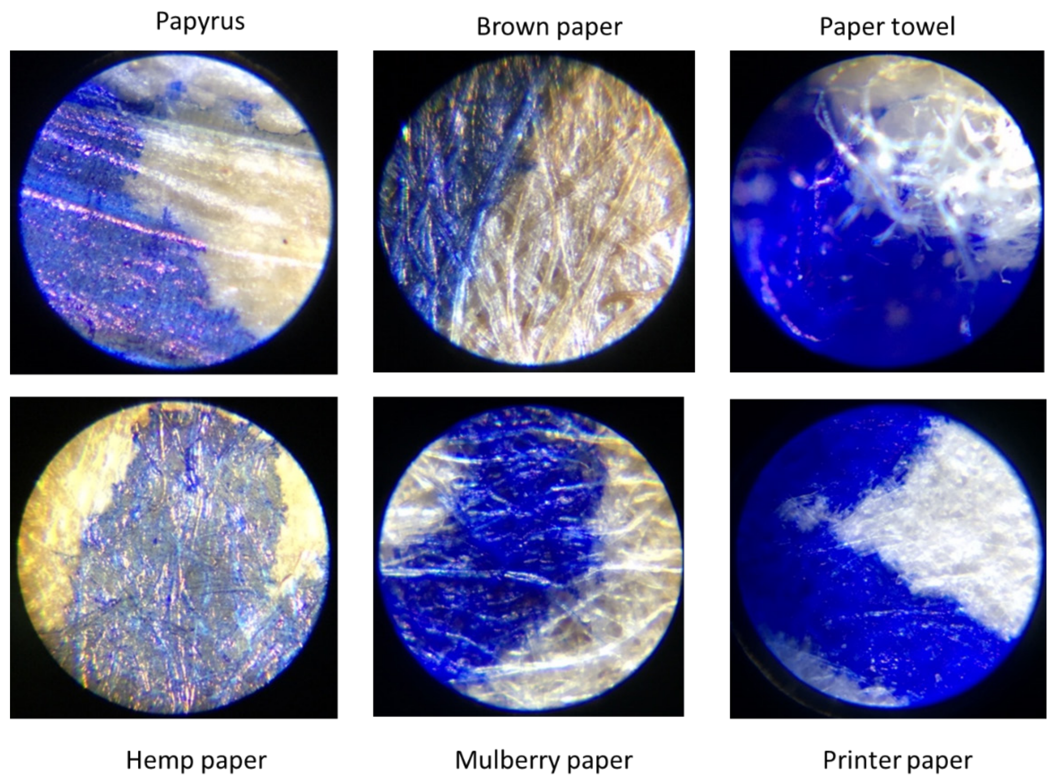


Fig. 8 Microscope images of blue ink (fine-point Sharpie) on various types of paper, 120× magnification

3. Activity #2: Watermarks

There are several interesting observations that students can make by looking at different papers. Many official documents such as US currency (Fig. 4) and official documents like student report cards use watermarks as security features. Some high-end papers also have watermarks. An example of a paper we used in our session is shown in Fig. 9. Students should be advised to hold the papers with watermarks up to a window or bright light so that the watermark will be visible. Watermarks are added to paper by pressing the image into the paper during processing. For more information on watermarks, the reader is referred to Wikipedia (2020a).

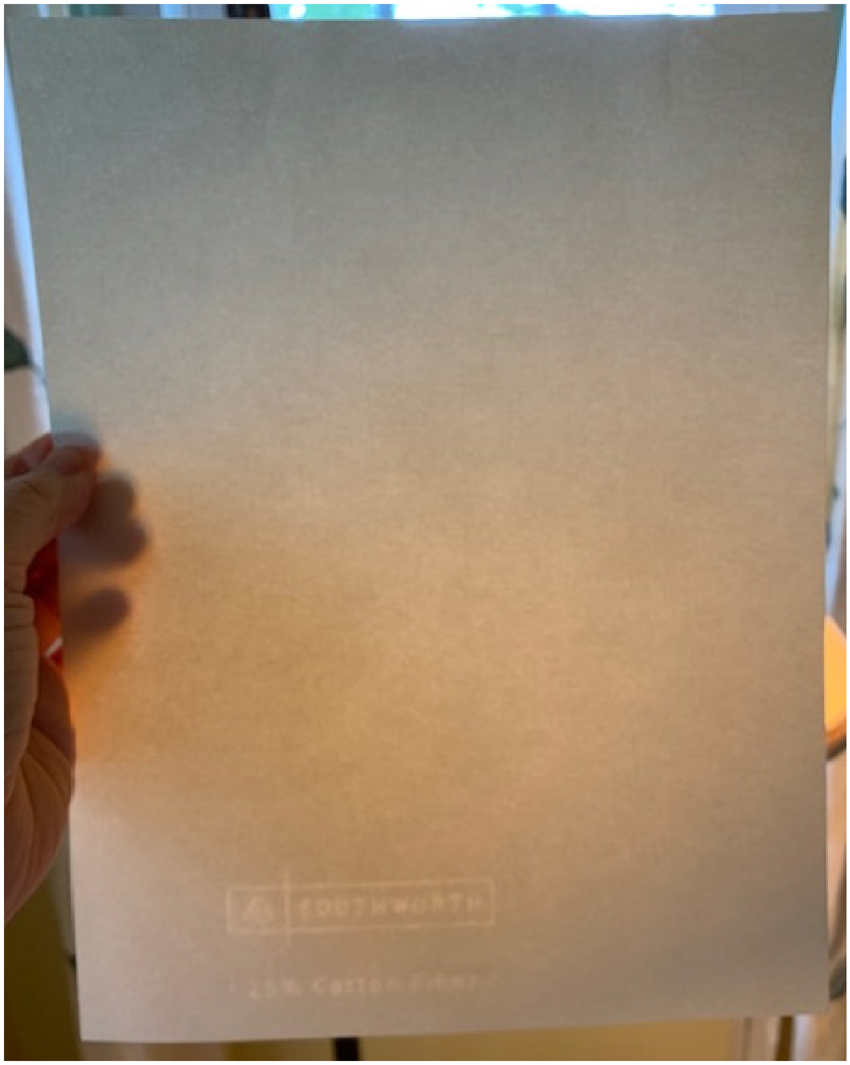


Fig. 9 Watermark on the bottom of a piece of stationary paper

4. Activity #3: Tear Test

Because of the way that paper is manufactured (see steps 10 and 11 in Fig. 2), fibers have a tendency to align in a certain direction. For printer paper, this preferred direction can easily be discovered by tearing the paper along its length and width, as shown in Fig. 10. When torn lengthwise, the paper tears smoothly with no change in direction. When torn widthwise, the tear tries to “correct” to the lengthwise direction. This test can be performed with waste paper from school, labels removed from soup cans, and so on.

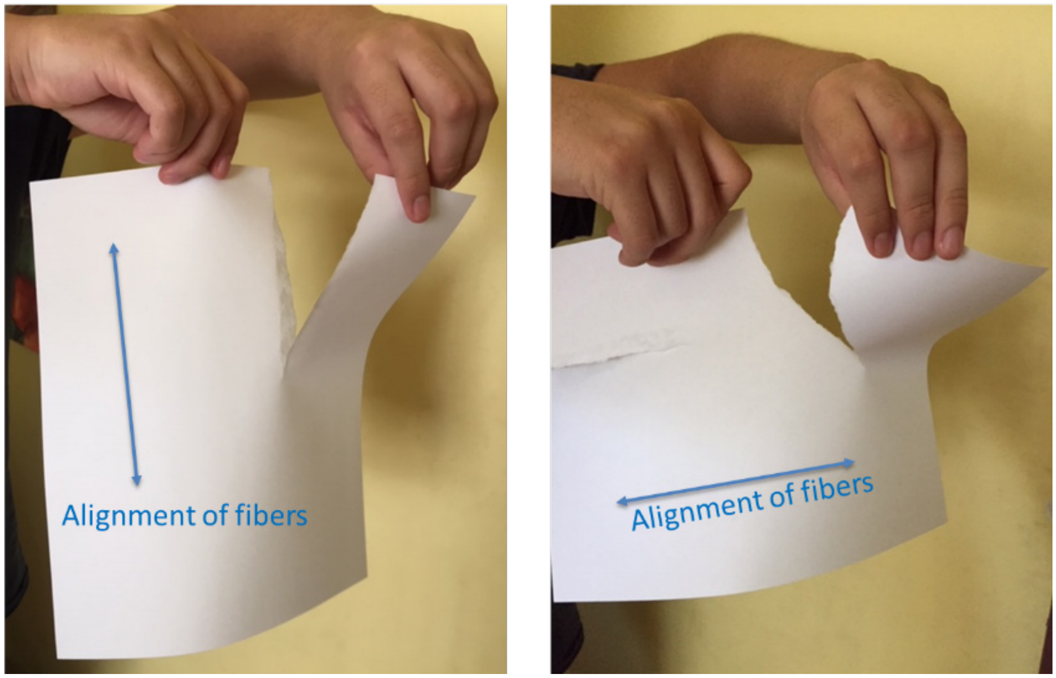


Fig. 10 Tear test to determine the direction of fiber alignment in paper

5. Activity #4: Smell Test

To conduct this test, simply have students smell several books. New textbooks will smell like the inks used to print them. Old books, especially those printed before 1980, have very unique smells. We found damaged paperbacks in the thrift store for $0.50 each that supplied specimens for hundreds of students with plenty of paper left over. The publication year 1980 is important because it was the year that publishers stopped using alum (aluminum sulfate hydrate [$Al_2(SO_4)_3 \cdot 18H_2O$]) in surface coatings. While alum is a wonderful multiuse ingredient (a deflocculating agent, sizing agent, bleaching accelerator, and clarifier) in paper production, over time it undergoes a chemical change and produces acid that decomposes the cellulose fibers in paper. A simplified explanation of the process is illustrated in Fig. 11, which shows cellulose units in circles, like beads on a necklace. Cellulose is a polymer made up of many monomer units (the "beads"). Acid can break oxygen-containing linkages, effectively "cutting the necklace". A single, well-placed cut in the middle of a polymer chain will cut it in half, thereby reducing its strength and setting off a chain of events ("popping off of monomer unit beads"), resulting in the release of small molecules that we can smell. One example of a small molecule shown in Fig. 11 is acetic acid (found in vinegar). As we discuss shortly, the presence of acids in paper can be determined by pH testing. Papers with a high lignin content will also produce molecules such as toluene, ethyl benzene, and furfural (Fig. 12). Furfural has an almond-like odor. A book's age can be estimated by the amount of furfural in its pages.

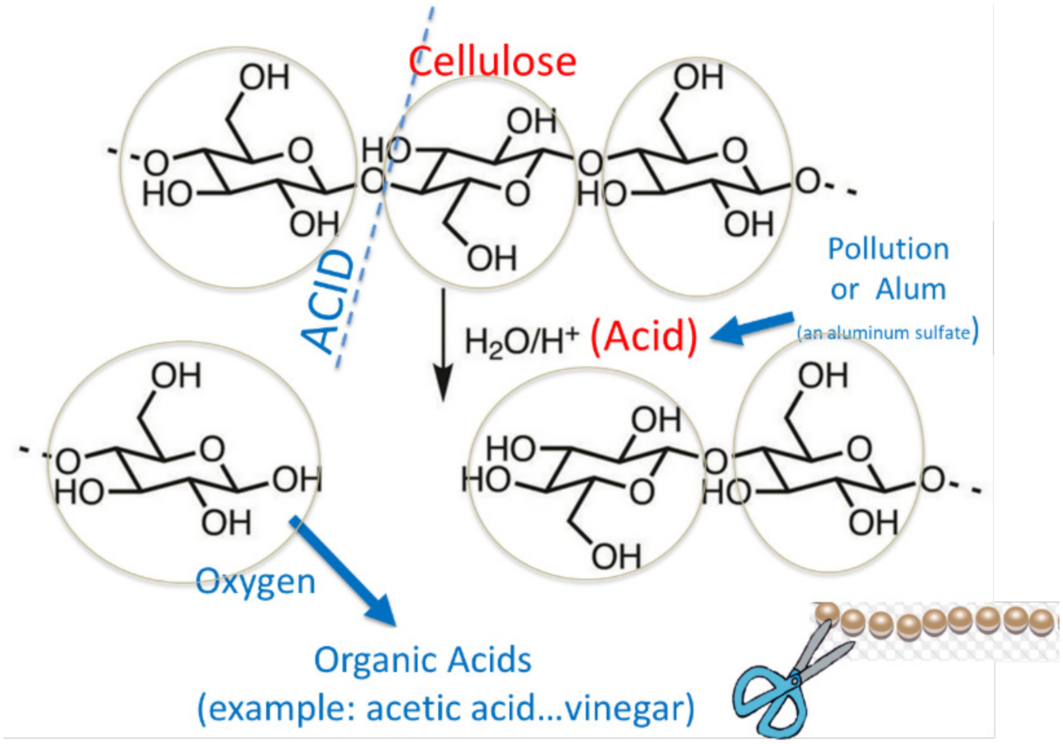


Fig. 11 Simplified mechanism for cellulose decomposition by acid. For an ultra-simple explanation for young children the analogy of scissors (acid) cutting a beaded necklace (the cellulose polymer) can be used.

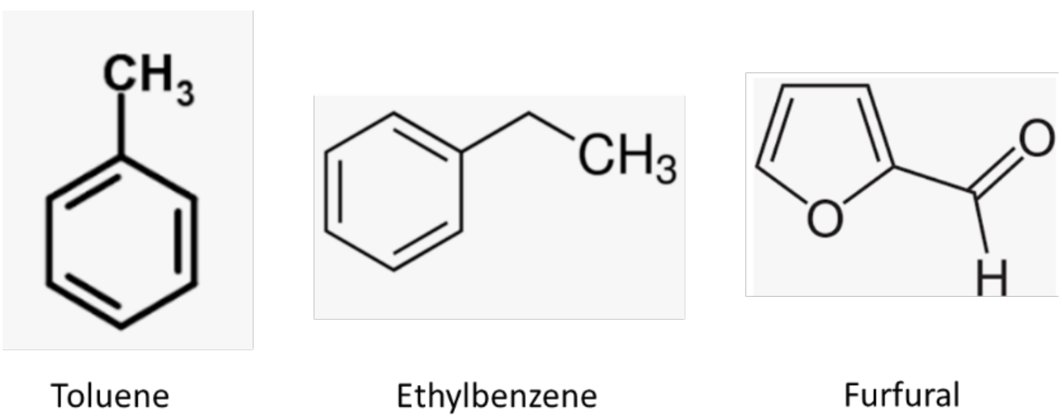


Fig. 12 Structures of toluene, ethyl benzene, and furfural

6. Activity #5: UV Light Test

Examination of papers under UV light will indicate those specimens containing optical brighteners (e.g., printer paper, index cards, and some types of loose-leaf paper). More information on optical brighteners can be found on Wikipedia (2020c). Low-cost, full-sized LED UV flashlights can be purchased from Walmart and other retailers for approximately \$6. When using these, yellow safety goggles should be worn. Low-power, mini-LED UV flashlights ("keychain" flashlights, Fig. 13) can be purchased from Amazon for approximately \$0.70 each when purchased in a lot of 50. The output is sufficiently low from these flashlights that yellow safety glasses are not required. Still, students should be advised not to shine it in their eyes or anyone else's eyes. Despite the low power, the mini-flashlights are sufficiently strong for the activities described. Some students may already have a similar mini-flashlight from "invisible ink spy pen" sets. Barnes & Noble offers such a pen/light combination for less than \$3. The effect of a mini-LED UV flashlight on several paper specimens is shown in Fig. 13. In Pesce-Rodriguez and Rodriguez (2019), we used this activity as part of a forensics program.

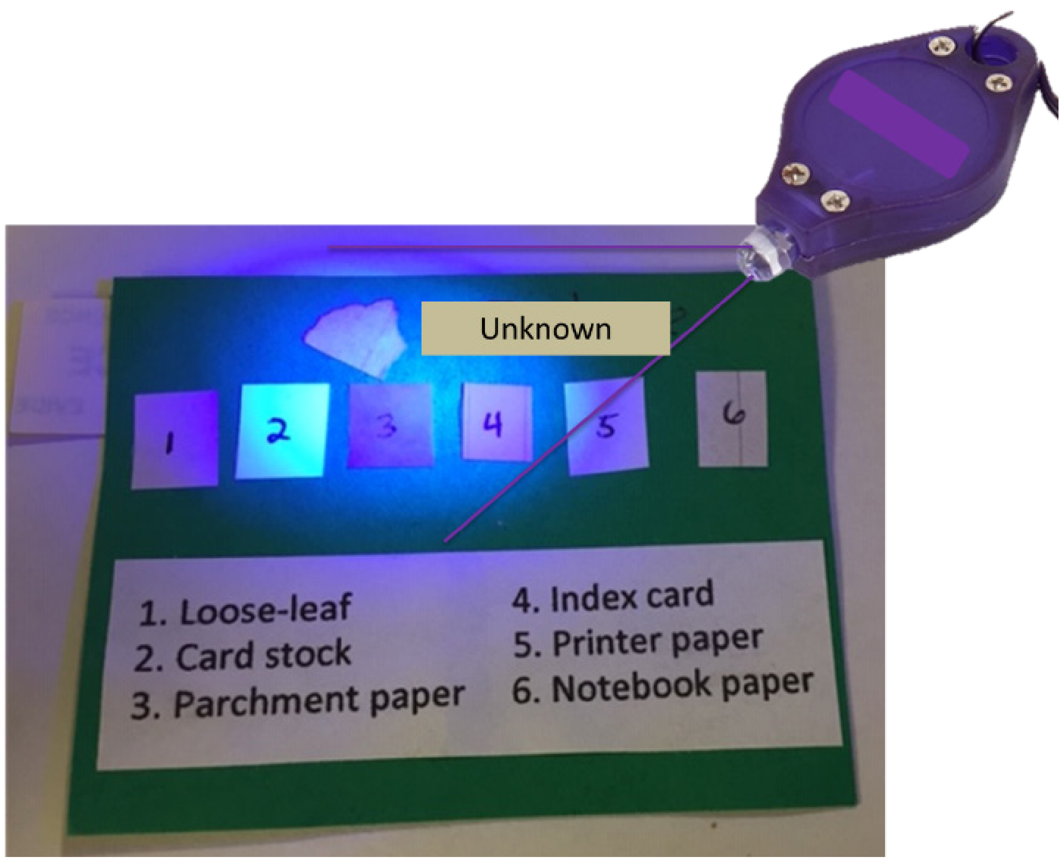


Fig. 13 Photo of several paper specimens under UV light

7. Activity #6: pH test

For activities 6, 7, and 8 (the pH, iodine starch test, and vinegar tests, respectively), the samples were placed on foam plates labeled with ballpoint pens. (Fig. 14) The labeling is easy and lasts through multiple wipings or rinsings with water. Foam plates are handy for containing small spills and protecting table and desk tops.

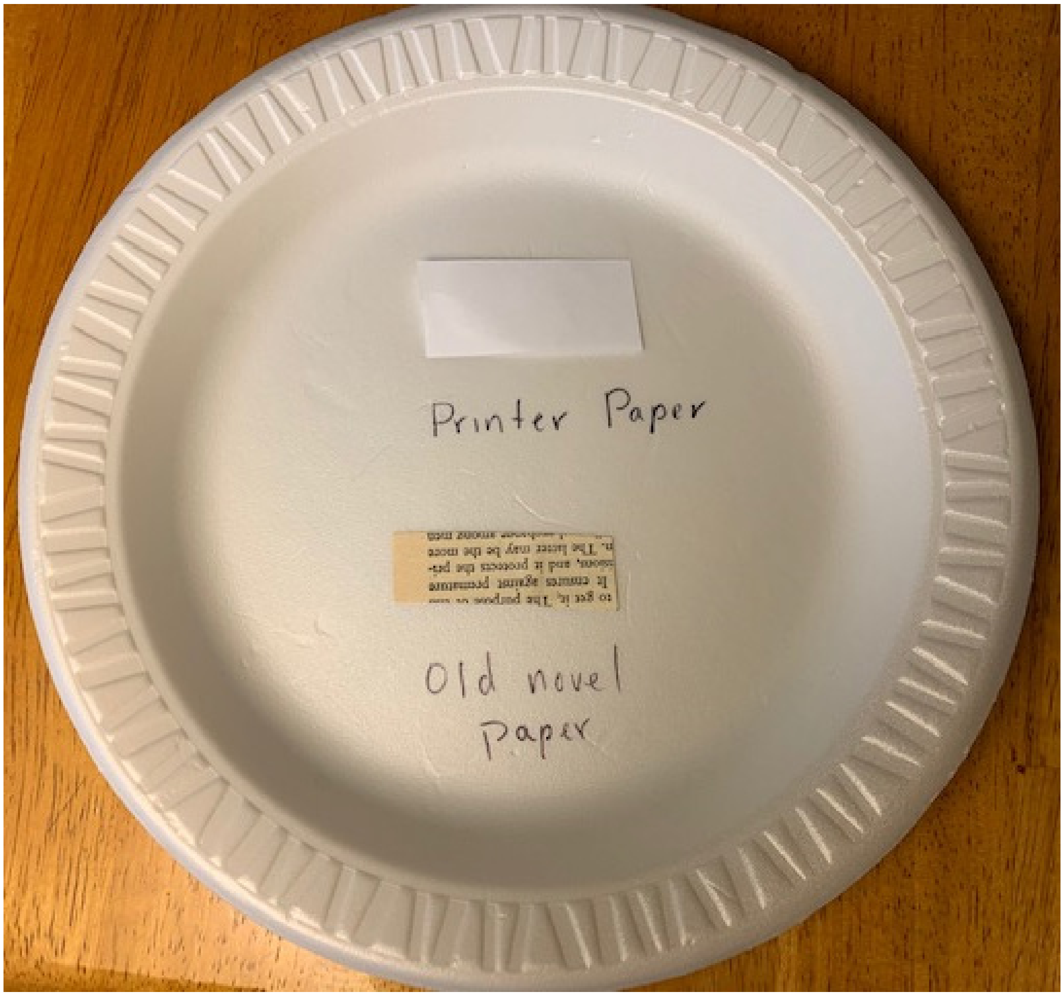


Fig. 14 Foam plate labeled with specimen names. The same specimens can be used for the pH, iodine starch, and vinegar tests (multiple spot tests on same piece of paper).

Depending on the types of paper chosen for this activity, it may be possible to tell something about their age with a simple pH test. For this, a liquid pH indicator is needed. Commercial liquid laboratory-grade universal pH indicators are available, but are relatively expensive and may expose students to potential toxins.

An alternate to commercial products is the juice of red cabbage, which works very well with a wide range of pH values. Demonstrations of the color changes associated with samples of various pH can serve as a lesson on its own. Common household items that can be used for this demonstration are citric acid (acidic; lemon juice or sour candies work well), vinegar (acidic), baking soda (mildly basic/alkaline), dish detergent (basic/alkaline), household ammonia (very basic/alkaline), and a cooled solution of boiling water with added baking soda (very basic/alkaline).

For preparation of a pH indicator from fresh red cabbage, first boil a small amount of distilled water (about 1/2 cup or 100 mL) in a small pot (water can also be microwaved), then turn off the heat and add 1 cabbage leaf (chopped). Allow the mixture to sit for 15–20 min, then collect the liquid. Store the liquid in the refrigerator if not being used right away.

Dried cabbage juice powder (Fig. 15) is also commercially available. We purchased the product from Educational Innovations (https://www.teachersource.com/product/red-cabbage-extract/chemistry) for about $11/bottle. The powder is handy to use since it can be prepared immediately before using. The extract is very concentrated and will last for years of classroom or homeschool use.

Fig. 15 Commercially available dried cabbage juice extract, reconstituted with water (right). Color/pH chart shown at bottom.

Whether preparing a cabbage juice indication from powder or fresh red cabbage, be sure to use distilled water when preparing. Distilled water can be purchased from most supermarkets at a very low cost (less than $1 for a gallon) and is well worth the price. We advise against using tap or well water, because they can often be alkaline enough to make it difficult to observe the pH of paper or other materials. Figure 16 shows the difference between cabbage juice prepared in distilled and tap water (from Baltimore City). According to the color chart in Fig. 15, cabbage juice is acidic (pink) in distilled water, but neutral (purple/blue) in tap water indicating that the tap water must be slightly alkaline (i.e., it raises the pH of the cabbage juice solution).

Fig. 16 Powder cabbage juice indicator made in distilled water (left) and tap water (right)

Another alternative indicator for pH observation is hibiscus tea; one common commercially available product is “Red Zinger” tea by Celestial Seasonings. The tea can be extracted into water or isopropanol (70%, rubbing alcohol) to make a concentrated solution. We have found that the extraction is faster in isopropanol than in water.

The range of color change observed for a number of typical household materials with both cabbage juice and hibiscus tea are given in Fig. 17. While both extracts change color in response to pH, we find the colors of the cabbage juice to be more vibrant and more appealing to students than those of the hibiscus tea.

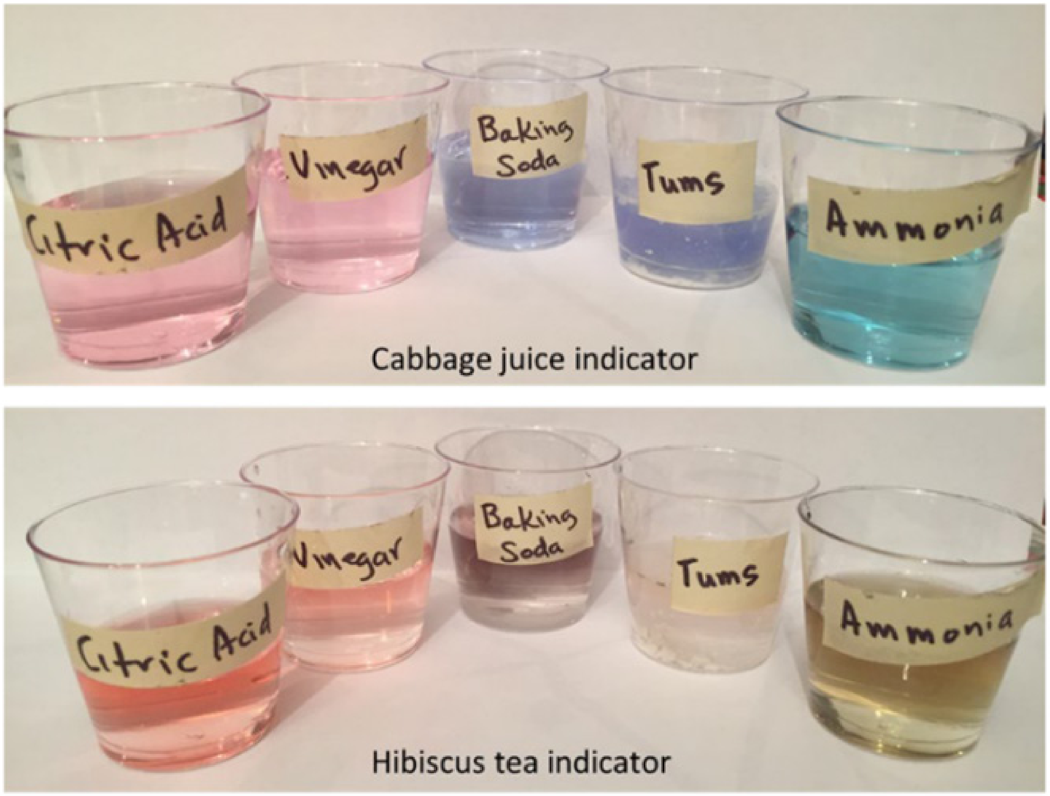


Fig. 17 Photos of various materials with added cabbage juice extract (top) and hibiscus tea (bottom)

The science behind the use of hibiscus tea or red cabbage juice as pH indicators is based on the chemistry of anthocyanins, which are natural compounds that are responsible for the color in many flowers, fruits, vegetables, and autumn foliage. More information can be found on Wikipedia (2020a).

When testing the pH of paper, students will find that modern paper such as printer paper and index cards will be basic/alkaline, while older paper such as that from an old book from the thrift store will be acidic (Fig. 18). The primary reason for this is the past practice (pre-1980) of using alum (aluminum sulfate) as a multiuse ingredient (a deflocculating agent, sizing agent, bleaching accelerator, and clarifier) in paper production. While alum worked wonders for the production of paper, it makes paper acidic and contributes to the hydrolysis (breakdown) of cellulose fibers, resulting in yellowing and “old book smell” (Strlič et al. 2009).

Fig. 18 Cabbage juice indicator on paper from an old novel (left) and new printer paper (right). The pink color on the old paper indicates that the paper is acidic and is undergoing degradation. The blue color of the new printer paper indicates that it is slightly alkaline (basic), suggesting that the paper will be stable for years to come.

Testing for pH of "mystery powders" in a forensic analysis is described in Pesce-Rodriguez and Rodriguez (2019) and of sand in Pesce-Rodriguez and Rodriguez (2020).

8. Activity #7: Iodine Starch Test

The iodine starch test for paper may be conducted using povidone–iodine solution diluted with water (1:3). The stock solution can be purchased from any pharmacy for about $6 per bottle. If kept in a cool, dry place, the contents can be used for years for chemical tests. The solution can be applied to the paper specimen by several techniques, including a dropper bottle, which can be purchased online at a modest cost and have the advantage of being well contained, or a plastic pipette ("dropper"), which is a cheaper alternative to a dropper bottle but requires the use of test liquid in an open cup (Fig. 19). Amazon offers 100 plastic pipettes for about $10. We rinse ours after each session and use them over and over again. A very inexpensive, readily available alternative to dropper bottles and pipettes is a plastic drinking straw. A small volume of the solution can be drawn up into the straw when placed in the liquid and will remain in the straw if a finger is placed over the dry end (Fig. 19). When the tip of the straw is applied to a specimen of paper, the liquid is transferred and absorbed. As with plastic pipettes, straws also require the use of test liquid in an open cup. We prefer to use dropper bottles in classroom setting for logistical and safety reasons. For home use, the other options are practical and cost effective.

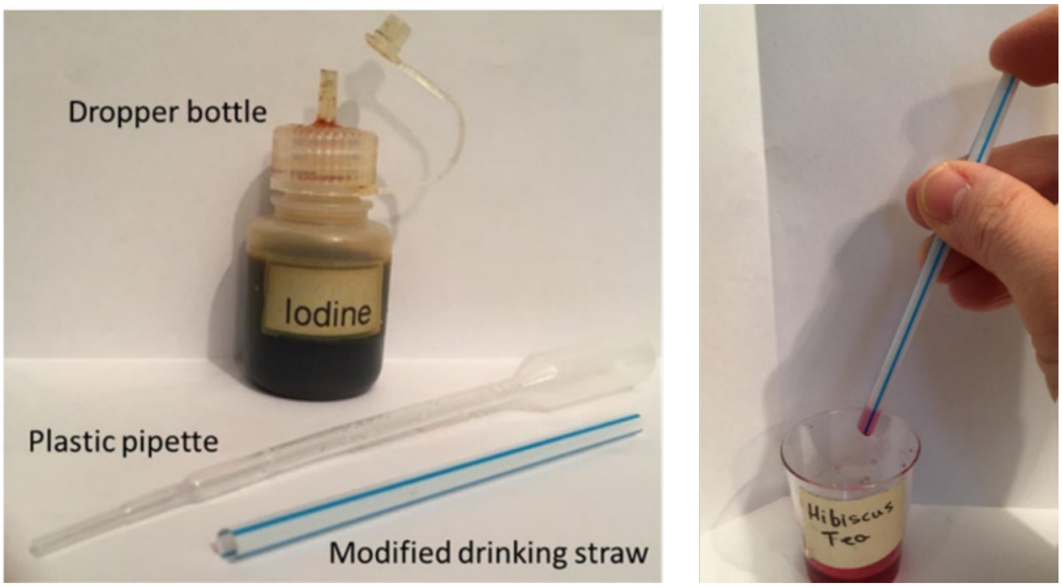
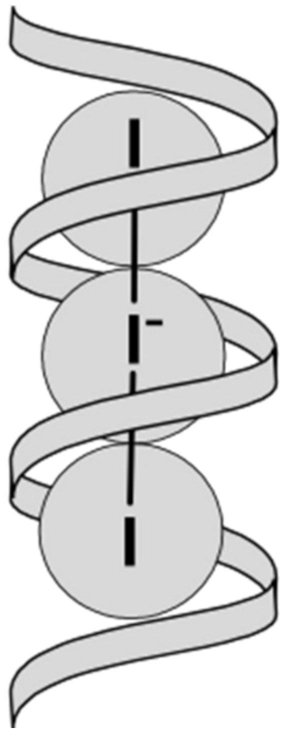


Fig. 19 Photos of several options for dispensing drops of reagents (left) and use of a plastic straw in place of a dropper bottle to dispense liquids dropwise (right) (Pesce-Rodriguez and Rodriguez 2019)

Reagent can be provided to students in 1-oz plastic cups. These can be purchased from several vendors. Amazon sells 100 for approximately $7. Labeling can be done with a dark permanent marker on light-colored masking tape (as in Figs. 17 and 19) or in sauce cups recycled from take-out meals (Fig. 16). Both types of cups can be used, washed, and reused many times. They stack together well and take up little space in storage.

A positive reaction for the iodine starch test is observed when the paper or other substrate changes color (orange/brown to black; Fig. 20). A simple explanation for the science behind the iodine starch test is that the color of iodine (I_3^-) is orange/brown when it is free in solution and black when within a starch helix as shown in Fig. 20. More details may be found on Wikipedia (2020b).



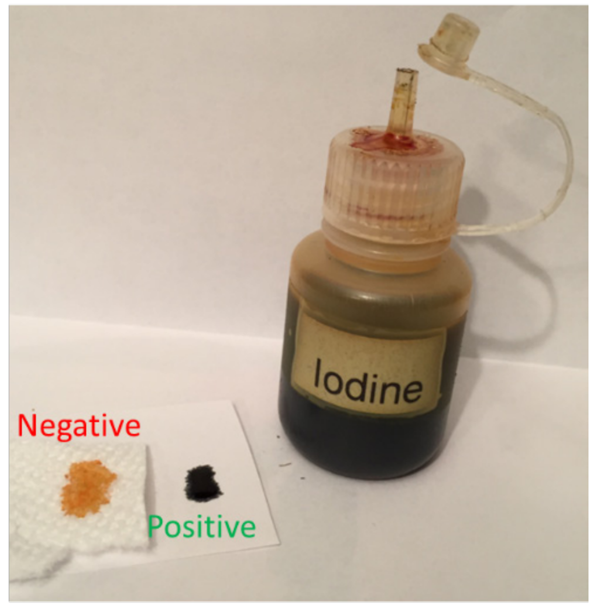


Fig. 20 Photo of a negative iodine starch response for paper towel (left, brown color) and positive response for printer paper (right, black color)

Paper specimens that respond positively to the iodine starch test are those to which starch sizing has been added to give a smooth surface finish. Printer paper and index cards will test positive for starch, but paper towels and toilet paper will not.

Note: While some individuals may report having an allergy to iodine, reports in the medical literature conclude that this is a myth (Dewachter and Mouton-Faivre 2015; Sampson et al. 2019). Iodine is an element that is essential to our health. It is true, however, that some individuals have experienced dermal sensitivity to iodine–povidone topical antiseptic. For this reason, instructors should be sure that students wash their hands in the rare event that contact with the dilute iodine solution occurs.

9. Activity #8: Vinegar Test (for Carbonates)

For this test, it is sufficient to test only two types of paper. We suggest paper from an old novel and new printer paper. One drop of vinegar should be added to each paper and then examined with a magnifying glass or preferably a mini microscope (see Fig. 5). The vinegar should react only with the printer paper, because only it has calcium carbonate in its surface coating.

When carbonates are present in paper's surface coating, bubbling will observed as the carbonates react with the acetic acid in the vinegar to produce carbon dioxide

(CO_2) gas (Fig. 21). While most students will not understand the chemistry involved, the reaction that takes place is provide for instructors who are interested in this information:

$$\mathbf{NaHCO_3 + CH_3COOH \quad \rightarrow \quad Na^+ (aq) + CH_3COO^- (aq) + H_2O + CO_2 (g)}$$

sodium bicarbonate + acetic acid → sodium acetate dissolved in water + carbon dioxide

(baking soda) + (vinegar) = (fizz)

Students can also try adding a drop of water to the printer paper to confirm that the bubbles are generated by vinegar, but not by water.

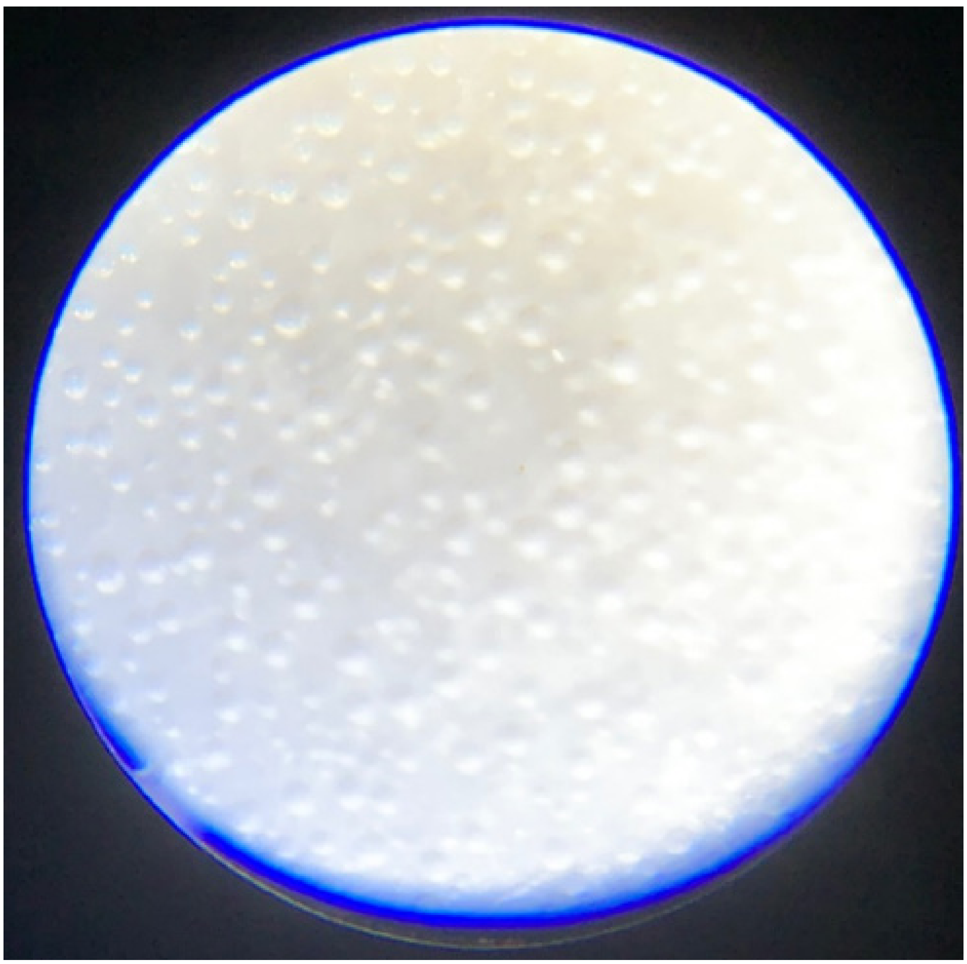


Fig. 21 Micrograph of printer paper through a drop of vinegar. Tiny bubbles of CO_2 are observed to form on the surface of the paper as a result of the reaction between the vinegar and calcium carbonate in the paper's surface coating. (Photo taken with a cellphone camera through viewer of microscope in Fig. 5.)

10. Activity # 9: Paper Chromatography

Paper chromatography is a very simple activity with very interesting science behind it. The level of explanation that accompanies the activity can be modified to suit the age of the student.

We start with a description of the activity itself, which is fairly simple. For the example shown in Fig. 22, 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, popsicle 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 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.

As soon as the paper towel strip touches the water, the water will be absorbed and begin to travel up the paper towel strip. As this happens, components of the ink may separate and be observed as different 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 then others. We find that students are most impressed when an ink separates into distinct colors. Crayola "Color Changeable" markers are particularly good for this activity because the ink in each marker is composed of two distinct colors.

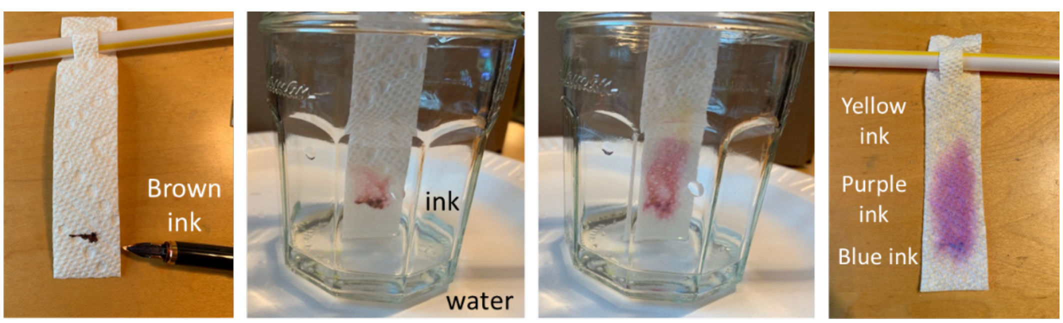


Fig. 22 Photographs of paper chromatography activity with a brown ink. Left to right: dry paper towel strip with ink mark; paper strip suspended in jar containing a small amount of water (water is rising up the strip carrying ink with it); same, after approximately 10 s; and strip after removal from the jar (ink colors separated into three components).

Now that we have discussed the mechanics of the activity, we turn to how best to explain to students the science behind it. A simple explanation we have often used is that there is a competition between the paper towel and the water (i.e., will the ink stick to the paper towel or "go for a ride" with the water?). For more advanced students, instructors can refer to the paper towel as the “stationary phase” and the water as the “mobile phase”. What determines whether the paper towel (stationary phase) or the water (mobile phase) wins that “competition” is whether the ink is attracted more to the towel or to the water. In the case of the example in Fig. 22, the blue ink does not travel at all, so is more attracted to the paper towel, whereas the yellow ink is more attracted to the water, so it “goes for a ride”. The purple ink is attracted to both the paper towel and the ink, so moves more slowly than the yellow ink. For more advanced students, instructors can explain that this basic technique is widely applied in the field of analytical chemistry. Chemist employ various forms of chromatography, including the following:

- Thin layer chromatography: Similar to paper chromatography but instead uses a layer of silica gel, alumina, or cellulose on a plastic or glass plate.
- Gas chromatography: The mobile phase is a gas, usually helium, while the stationary phase lines up, or is packed into, a long column.
- Liquid chromatography: The mobile phase is a liquid (can be water or other solvents) and the stationary phase is a solid and packed into a short column (relative to that used in gas chromatography).

Advanced students may be interested to understand more about why inks or other materials analyzed by chromatography are attracted to mobile or stationary phases. We focus on one critical aspect of this topic: hydrogen bonding in water. To begin, we consider the chemical composition of water. Some students might know that the water molecule can be represented as “H_2O”, where the “H” represents a hydrogen atom and the “O” an oxygen atom. The subscript “2” indicates that water has two hydrogen atoms. So, water could also be represented as “H-O-H”.

A cluster of water molecule models is shown in Fig. 23. In each water molecule model, O is red and H is white. In each model, we see that water is not a linear “H-O-H” molecule, but instead almost L-shaped, with hydrogens on two corners of a tetrahedron and what appears to be nothing on the other two corners. Actually, those corners are occupied by two “invisable” pairs of electrons.

The water models in Fig. 23 (https://www.3dmoleculardesigns.com/Education-Products/Water-Kit.htm) are special in that they include hidden magnets that simulate the “polarity” of the molecule. A full explanation for why this polarity exists is beyond the scope of this report, but we again offer a very simple explanation that seems to help many younger students grasp the general concept. Because of the electronic structure of oxygen, it is very “eager” to “borrow” two electrons from anywhere it can (O has six electrons in its outer shell and wants to have two more for a total of eight electrons, a “full shell”). If O were to have a personality, it would be "needy and greedy" because it so badly wants those two electrons. It is this nature of O that allows it to oxidize carbon (including combustion) and metals (including rusting). As opposed to "needy greedy" O, H has just one electron. It is "happy" to either give that one up or take one more. When up against "needy greedy" O, H gives in to the bully and shares its electron. In a water molecule, when hydrogens "share" their electrons with oxygen, it is not in a "fair" manner; afterall, oxygens are greedy! The consequence of this unequal sharing of electrons (which carry a negative [–] charge), is that the oxygen become "partially negative" and the hydrogens become "partially positive". If we consider the "+" and "–" to be like the poles of a magnet, we begin to understand the concept of "polarity", and we can also understand why in Fig. 23 all the white "partially positive" hydrogens are attracted to the red "partially negative" oxygens. The partial charges on H and O are responsible for what scientists call "hydrogen bonding". While two H atoms are covalently bonded to a single O atom through their shared electrons to make a single molecule of H_2O in the models in Fig. 23, all the hydrogens and oxygens are attracted to each other by hydrogen bonds. Hydrogen bonds are much weaker than covalent bonds, but are still strong enough to keep H_2O molecules together in the solid phase (ice) and liquid phase (water), as in Fig. 23.

Fig. 23 Photo of magnetic water molecules showing hydrogen bonding that attracts water molecules to each other

Hydrogen bonding also results in strong interactions between cellulose and water, as shown in Fig. 24. When molecules such as water are attracted to molecules like themselves, the interaction is called "cohension". When they are attracted to a molecules that are different than themselves (for example, cellulose), the interaction is called “adhesion”. In Fig. 25, we see both cohesion and adhesion of water. The latter interaction with cellulose fibers results in the movement of water molecules along the fiber direction. It is this behavior that we observe in the paper chromatography activity in Fig. 22. Water molecules move up the strip of paper towel. Some ink molecules are attracted to the water (they are hydrogen bonded to the water) and “go for a ride” with the water (the mobile phase), while others are not attracted to the water and remain where they were deposited on the cellulose fiber in the paper towel (the stationary phase).

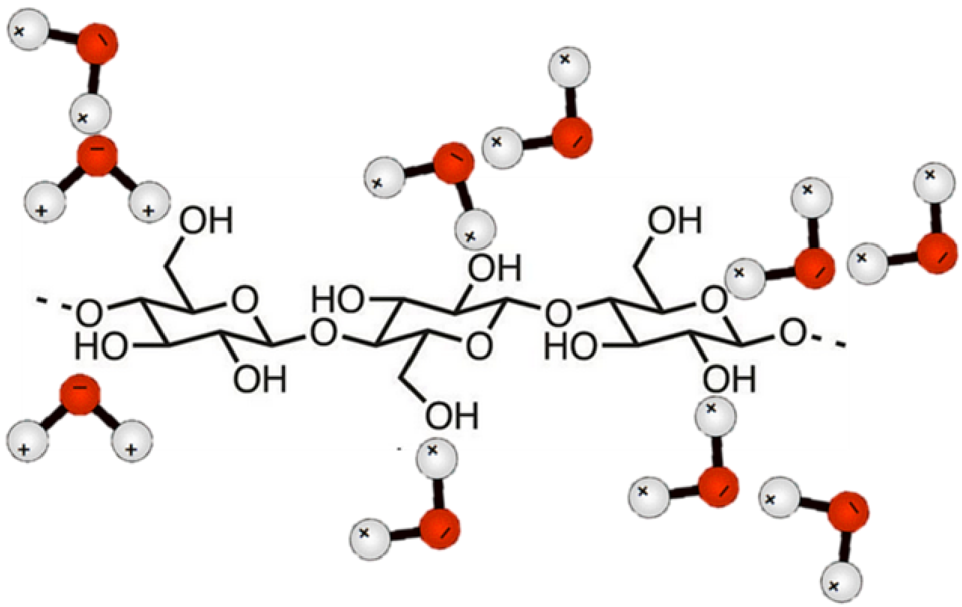


Fig. 24 Cartoon of water molecules showing hydrogen bonding that attracts water molecules to each other and to cellulose

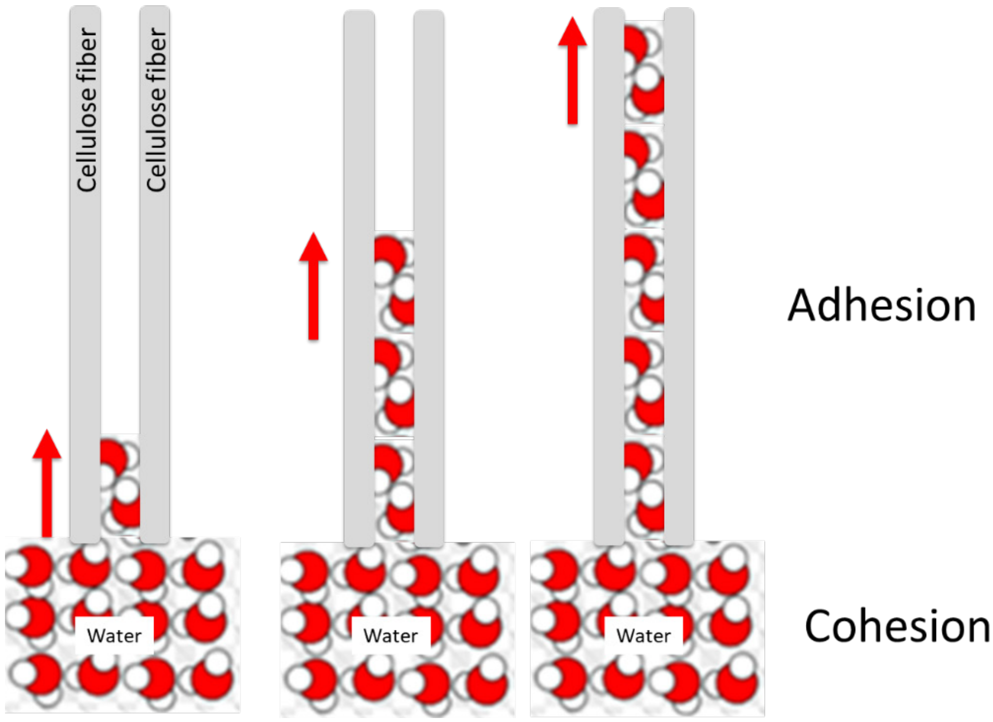


Fig. 25 Cartoon showing water attracted to itself (cohesion) and water attracted to cellulose fiber, as in paper towels (adhesion) because of hydrogen bonding

11. Activity #10: Making Paper

We give some very general guidance on making paper from waste paper, for more specific details download the following publication (ACS 2019): (https://www.acs.org/content/dam/acsorg/education/outreach/celebrating-chemistry/2019-ccew-celebrating-chemistry-english.pdf).

To make paper, a source of paper pulp is needed. This can come from waste paper (we used junk mail) that is first soaked in water and then turned into a slurry with a blender. If a blender is not available, paper can be soaked a bit longer and then “raked” with a fork or beaten with a meat tenderizing utensil. This can be a very tedious if preparing pulp for a large group of students. Dryer lint can also be used, as can a combination of waste paper fiber and dryer lint. Decorative papers can be made by adding bits of colored paper or glitter to the pulp.

After obtaining a slurry in a blender, we strained the mixture using a kitchen strainer and filled plastic shot glasses with a sufficient amount of pulp for use in the mini papermaking set (as in Fig. 26, left). We purchased the mini papermaking sets (trays, deckles, and deckle liners) online for approximately $7 each and used the method recommended by the vendor (Fig. 26, right). Water was provided to students in a 9-oz plastic tumbler (filled approximately half full). The same tumbler was used to collect excess water after the paper had been pressed. We found the size of the kit to be appropriate for classroom use. To minimize messes, we provided a small towel (face cloth) and a small sponge for each student that were used to help dry the paper and wipe up any spills.

Fig. 26 Mini papermaking kit (ARTEC product no. 002649) including tray (yellow), deckle (blue) deckle liners (2), and plastic sheet

There are many online sites that give direction for homemade deckles for paper making. Figure 27 (right) shows our homemade deckle made by stapling a piece of replacement window screen (sold by the roll at home improvement stores) to an old picture frame. We used a shallow cookie pan under the deckle to collect water as the pulp was pressed. A photo of one of the papers we produced is shown in Fig. 27 (left). We found that using a piece of window screen material on top of the paper pulp is useful when flattening the pulp and pressing water from it. The window screen material leaves a nice pattern in the paper, and since the screen does not stick to the pulp, it facilitates removal of the wet paper from the deckle.

Fig. 27 Photos of homemade papermaking deckle and the sample of paper produced

Freshly made paper takes time to dry. In our library program, we provided each student a piece of felt that was just larger than their homemade paper to keep the product flat during their trip home.

12. Conclusion

This report provides a very brief history of materials the ultimately led to the paper products that we use today. Through a series of 10 hands-on activities, students will gain a greater appreciation not only for how paper is made, but of the chemical and physical properties of paper. All activities can be carried out using inexpensive supplies that are either readily available, or can be purchased online for a modest cost. The activities can be mixed and matched according to the interest and abilities of a given class. Some activities overlap with other programs in our series and can be used in programs focused on other topics, including pH, acid-base chemistry, and microscopy.

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List of Symbols, Abbreviations, and Acronyms

$Al_2(SO_4)_3 \cdot 18H_2O$	aluminum sulfate hydrate
ARL	Army Research Laboratory
ACS	American Chemical Society
CCDC	US Army Combat Capabilities Development Command
CCEW	Chemists Celebrate Earth Week
CO_2	carbon dioxide
H	hydrogen
H_2O	water
LED	light-emitting diode
O	oxygen
STEM	science, technology, engineering and mathematics
UV	ultraviolet

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