Clean Water through Chemical Engineering: Introducing K-12 Students to ChE Using Filtration

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Abstract

The authors have developed a lesson plan on water filtration to introduce K-12 students to chemical engineering through hands-on activities. The primary motivation for developing the lesson was to hook K-12 students into the societal impact of chemical engineering in addressing the grand challenge of providing access to clean water. Our secondary motivation was to develop outreach materials related to our research on transport in pores and microchannels. The full plan was developed as part of a graduate course at the University of Illinois at Urbana-Champaign on science and engineering outreach in consultation with middle school teachers and tested in middle school classrooms and an after school program in a Boys & Girls Club. Activities from the lesson plan have been used separately in several outreach activities since 2011 including multiple Girl Scout events for 6th-12th graders, a professional development workshop for K-12 science teachers, and a summer camp for 4th-8th graders and their grandparents. The lesson begins with a discussion of challenges of purifying polluted water and drinking water supplies in developing nations. Then a series of activities demonstrate how chemical engineering principles and technologies are effective in cleaning water and how they can be used to enhance access to purified drinking water. This lesson is designed to be completed in one 1-hour period with two experiments and one physical activity. For more mature students, an inquiry-based experimental activity for designing a new filter is also provided. The goal of this paper is to disseminate the lesson plan and all the associated documentation to other educators and to provide some ideas for adapting the lesson to a variety of audiences.

Introduction

Water filtration is an engineering process with great societal benefits and clear connections to several engineering disciplines. Design and deployment of water filters is a popular topic for engineering service learning courses and trips[1-5], philanthropic efforts such as Engineering Without Borders[6], and collegiate engineering design and laboratory courses[7-12]. Engineering-related curricula about water have been developed for use in K-12 classrooms and outreach events[13-15]. We sought to develop inexpensive activities using household materials that could demonstrate chemical engineering separations concepts connected to our teaching and research interests in fluid mechanics, mass transfer, and biomedical engineering. Additionally, we developed a physical game as an analogy for particle motions through pores of different sizes with various surface properties. We have not seen documentation of a similar game in any of the filtration educational materials published or distributed elsewhere. The lesson plan presented here was developed a part of a graduate course titled Introduction to Science Education for scientists and engineers at the University of Illinois at Urbana-Champaign. The course was designed to train graduate students how to develop educational activities that connect to K-12 science standards and that contribute to desired societal outcomes consistent with the National Science Foundation Broader Impacts proposal review criteria. This paper is written as a means for disseminating the lesson plan to provide other instructors access to the lesson activities, which they can then adapt as desired. Instructional PowerPoint files for student use and background information for teachers are available in the lesson plan zip file available on our website[16]. At the end of this paper, we describe some of our experiences in adapting the materials for a variety of contexts.

Lesson Plan Learning Objectives

After completing this lesson, students will be able to

- Define filtration and pores. Filtration is a process for removing contaminants from a liquid by passing it through some medium called a filter. Pores are openings or holes in the filter medium and are important for separating solid contaminants.
- Describe differences between mechanical and chemical filtration. Mechanical filtration depends on pores to block solid particles that are larger than the pores from flowing through the filter with the liquid. Chemical filtration depends on interactions between dissolved molecules in the liquid and the surfaces of the filter materials. Dissolved molecules can stick to the filter medium and are unaffected by pore size.
- Identify which filters from a given list of common filters use mechanical or chemical filtration to separate solids (mechanical filtration) and dissolved contaminants (chemical filtration) from dirty water or air. The list should include coffee filters, colanders, air conditioner filters, swimming pool filters, fish tank filters, and kitchen sink water filters. The first four in the list involve mechanical filtration. Fish tank filters generally use chemical and mechanical filtration, and kitchen sink water filters primarily use chemical filtration though they may have additional mechanical filters to block solid particles from clogging the chemical filters.

Higher level learning objective for advanced students

After completion of the optional activities under the Elaborate section, students will be able to

- Define an experiment to test the efficiency of a water filter.

Instructional Activities

Overview

The following lesson plan is organized into four sections: engage, explore and explain, elaborate, and evaluate. The bulk of the activities are under the “explore and explain” heading. In the first experiment (Figure 1), cornmeal is separated from water by passing water contaminated with cornmeal and food coloring through a simple filter made of a cotton ball (a paper coffee filter may also be used). This is an example of size-based or “mechanical filtration.” In the second experiment (Figure 1), students learn that food coloring can also be removed from water in a process called “chemical filtration” (adsorption). Students test two types of materials: glass beads and activated carbon. Glass beads do not interact with food coloring and do not remove the coloring from water. Activated carbon interacts with food coloring and removes it from water making the water clear again. Activated carbon is a very common material for removing organic contaminants and is used in many devices, such as household water filters and pool and fish tank filters. Materials from devices with built-in filtration systems may also be compared as an optional component (under the “elaborate” heading). The physical activity involves students hopping on one foot through pathways marked on the floor as they pretend to be contaminant molecules moving through pores in a filter. Wide and narrow pathways simulate mechanical filtration. Pathways marked with double-sided tape simulate chemical filtration.

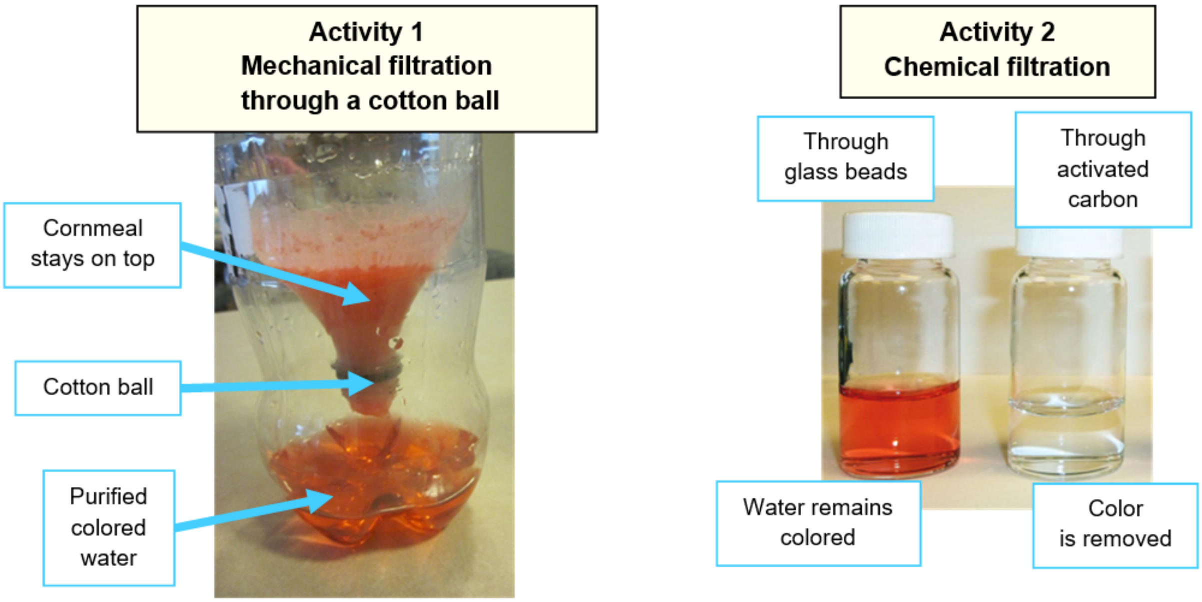

Figure 1: Experimental activities for demonstrating mechanical and chemical filtration.

Activities

Engage: *(5 minutes)* Hook students' attention in the topic by showing them a bottle or glass of water or images of other fresh water sources. Ask whether they would (or could) drink water from any of these sources. Then pour at least one cup of the water into a beaker or clear container, add several tablespoons of cornmeal, and a few drops of food dye to the water. Ask the students if they would drink the water now (hopefully not). Show images of dirty water sources. Ask the students if they would drink water from any of those sources. Explain that in this country assumptions are made about the purity of our drinking water, but many people around the world do not have that luxury.

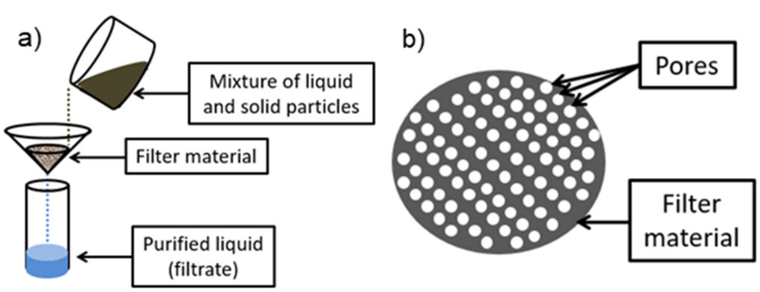

Figure 2: Illustrations to define a) filtration and b) pores.

Ask the students if they know of any places where filters are used (pools, oil and water filters in cars, vacuum cleaners, coffee makers, fish tanks). Have them list at least three filters. Explain that engineers and scientists have found ways to purify water and air, and that in this lesson they are going to try some of these methods. Introduce the words "filtration" and "pores" using Figure

2. Ask the students why they think it is important to be able to make water pure again (it is necessary to keep our water streams clean; it is often necessary to purify water that we get from natural sources to make it drinkable). Applications from water treatment, gas separations, and filtration of blood by kidneys and dialysis machines can be discussed here. If possible, pass around any examples of these common filters that you have available. Pass coffee filters around to the class. Ask students what they notice about the filters when held up to the light (Figure 3a). They should observe small holes in the filters. It should be emphasized that these holes are called "pores." Also show the students a colander (visible pores) and a cotton ball. Stretch the cotton fibers apart to reveal the pores of the cotton ball (Figure 3b).

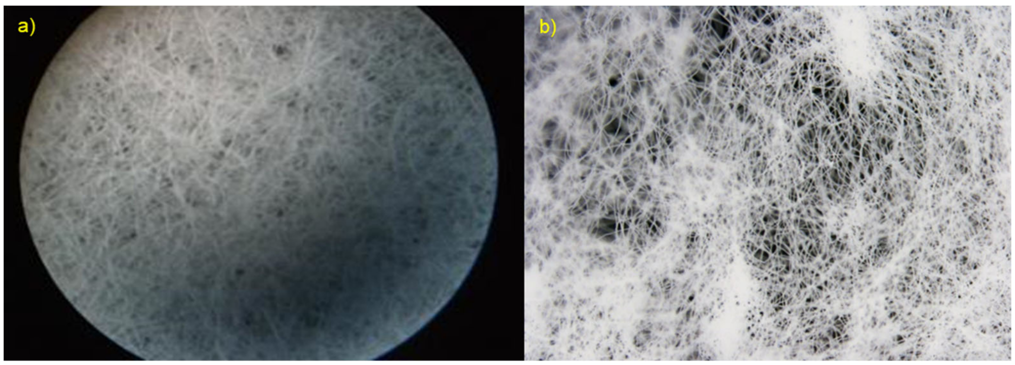

Figure 3: Light microscope images of a) paper coffee filter and b) cotton ball.

Additionally, if time allows, an explanation or video of the water treatment process could be provided illustrating the types of filtration and purification steps involved in drinking water and waste water applications. Alternatively, a tour of a local water treatment facility could be conducted to demonstrate these concepts and to expose students to science and engineering careers available in most municipalities.

<u>Explore and Explain</u>: *(45 minutes)* Students will have the opportunity to try purifying their own mixtures of polluted water using two filtration methods in the following activities. We recommend for the activities to be conducted in small groups. All of the activities involve common household, food grade products that are safe to handle. However, students can be encouraged or required to wear gloves or safety glasses or goggles to prevent food coloring messes and to get in the mode of a scientist by wearing relevant personal protective equipment.

<u>Activity 1</u>: (10 minutes) This activity involves filtering polluted water with solids through a cotton ball. Introduce mechanical filtration (Figure 2a). The class should be shown the general setup of the filter device (Figure 1). Our online documentation [link to be provided after paper is unblinded] includes step-by-step details and tips for the setup are given in the Teachers Notes Mechanical Filtration Experiment Setup Tutorial PowerPoint file, procedures for students to follow during the experiment are provided in the Classroom Slides PowerPoint file, and student assessment questions are provided in both the Filtration Fun Lesson Plan document and the Classroom Slides PowerPoint file. Students should be asked to make predictions regarding what they think will happen to the water, the cornmeal, and the color of the water. Have the students record their observations about the water + food coloring + cornmeal mixture after it has passed through the cotton ball (Figure 4a). Expected results are that cornmeal should stay on top of the cotton balls (Figure 4b), but water should pass through the cotton balls to the bottom of the bottle

and should remain colored (Figure 4c). Do not discard the liquid collected in the bottom of the bottles; it will be used for the next activity.

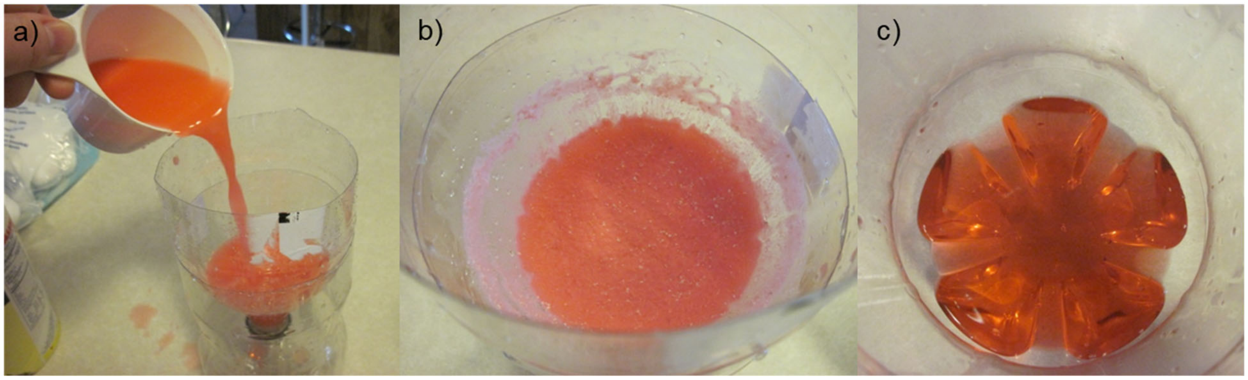

Figure 4: Mechanical filtration activity: a) pour the mixture of food coloring, water, and cornmeal over an inverted half soda bottle stoppered with a cotton ball and collect the filtrate in the other half of the bottle, b) the top half of the bottle has a residue of colored cornmeal above the cotton ball after the liquid drains completely, and c) the colored liquid passes through the cotton ball to be collected in the bottom half of the bottle.

<u>*Explain Activity 1*</u>*: (5 minutes)* Explain that water contaminated with cornmeal and food coloring is a mixture that can be separated into its individual components physically. Explain that the cotton balls have pores where substances can pass through. Remind the students of the definition of a *pore* as an opening in the filter—either a hole in an object or a gap between objects like rocks or beads. Explain to students that the important variable for determining whether a component in a solid and fluid suspension mixture can be separated is the size of solid particles relative to the size of the openings in the filter. Liquid can pass through the pores because it can take any shape. Solids, however, cannot change shape and will stay on top of the filter if the pores are smaller than the solid particles. This is analogous to a person trying to squeeze through a doggie door. Sometimes those pores may not be visible to our eyes, but we know they are there because water can pass through. We can also infer that plastic food wrap does not have any pores in it because it does not let water through. A colander has very large "pores" that are bigger than pieces of cornmeal that we want to separate, and both the particles and the liquid pass through it easily. The food coloring is not removed because it is dissolved in water, i.e., there are no solid particles of food coloring, but there are molecules of food coloring dispersed in water.

For younger learners, show the students an object with large pores (holes), such as a strainer and a material with no pores, such as plastic food wrap. Ask them whether they think either of these items can be used to separate cornmeal from water. A quick demonstration can be performed. Ask the students why they think separating cornmeal from water is possible with a cotton ball, but impossible with a colander or plastic wrap (pores in the cotton ball are smaller than grains of cornmeal, pores in a colander are bigger than grains, plastic wrap has no pores at all and water will not flow through).

<u>*Active Explanation Demo*</u>*: (5 minutes)* To get students active and engaged in the explanations and understanding the concepts presented, the following demonstration can be used. It also serves a bridge between Activities 1 and 2. Before the session, set up three pairs of tape lines (~8-10 ft. for each line) on the floor using masking tape. The first pair of lines should be spaced

about 8 inches apart. Label the space between the first pair of lines as “pore #1.” The second pair of lines should be spaced about 4 inches apart. Label the space between the second pair of lines as “pore #2.” The third pair of lines should be spaced about 8 inches apart. Label the space between the third pair of lines as “pore #3.” The lines in pore #3 should be marked with double-sided tape (or masking tape flipped upside down) with an exposed adhesive top layer.

Figure 5: Participants hopping through “pore 1” in the active explanation demo.

Demo Part 1: Have the students hop on one foot through pores #1 and #2 single file without touching the tape.

Reflection Part 1: Ask the students to compare their experiences walking through pores #1 and #2. [They should find pore #1 very easy. Pore #2 will be more challenging or impossible, depending on the size of their shoes.] Ask them to describe how this activity relates to pores and solid particles. [These two “pores” illustrate the difference in pore size for solid particles of the same size.] The analogy can be made to coffee grounds not fitting through the pores in a coffee filter but easily passing through a colander. Similarly, the cornmeal in Activity 1 would move through a colander’s pores but not through the spaces between the fibers of the cotton balls.

Demo Part 2: Have the students hop on one foot through pore #3. If they touch the double-sided tape, they stick to it. Have additionally double-sided tape available, as this may need to replaced mid-activity, depending on the number of students.

Reflection Part 2: Ask the students to compare their experiences moving through pores #1 and #3. [They should find pore #1 very easy, but pore #3 should be sticky if they touch the edges.] Ask them to describe how this activity relates to pores and filtration. [This is an analogy to molecules that could otherwise fit through the pore being stuck to the pore surfaces.] The “sticky” surfaces are due to attractions—either chemical bonds or electrostatic interactions—between the pore surface and the molecules.) The use of “sticky” surfaces for filtration will be explored further in Activity 2.

<u>*Activity 2*</u>*: (15 minutes)* Ask the students why the liquid in activity 1 remained colored (a typical answer: because it is colored water or because more cotton balls are needed to absorb the color). Explain that molecules of the food dye are much smaller than grains of cornmeal and smaller than the pore size in mechanical filters and pass through the pores easily. Ask the students if they

think it is possible to separate the food dye molecules and make water clear again (a typical answer: no). Remind them of the active explanation demo: even if the molecules are small enough to run through the pores, they can still be removed if they stick to the walls of the pores. In this activity they will learn which materials are sticky for food coloring molecules.

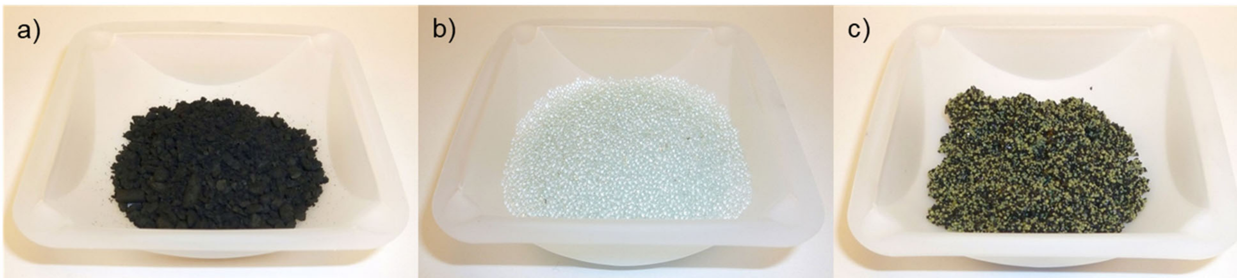

Figure 6: Materials for the chemical filtration activity: a) granulated activated carbon, b) 1 mm diameter glass beads, and c) contents of a water filter cartridge (for standard Brita pitcher models).

Pass around samples of materials that students are going to filter colored water through (Figure 6). If the material from the Brita cartridge is to be tested along with carbon and beads, show the students a Brita pitcher and ask them to identify it. Show them a filter cartridge that has been cut open. Display the filter cartridge material (Figure 6c), which is referred to here as “Brita granules” and consists of grains of activated carbon mixed with small yellow beads called ion-exchange resins. The filter cartridge material will be referred to here as “Brita granules.” Note: other brands of filter pitchers, such as Pur or GE, can be used as well, but appearance of materials and filtration results may vary. All our tests were carried out with the contents from a Brita cartridge. Assign each material (glass beads, activated carbon, and Brita granules, if used) to different groups. Students or the instructor can set up the filters for this activity (Figure 7a and b). Our online documentation [link to be provided after paper is unblinded] includes step-by-step details and tips for the setup are given in the Teachers Notes Chemical Filtration Experiment Setup Tutorial PowerPoint file, procedures for students to follow during the experiment are provided in the Classroom Slides PowerPoint file, and student assessment questions are provided in both the Filtration Fun Lesson Plan document and the Classroom Slides PowerPoint file. Students should be asked to make predictions regarding what they think will happen to the color of the water using the material assigned to their group. Have the students record their observations after using the chemical filter with their material (Figure 7c and d).

Expected results (Figure 8): The glass beads should give a colored water solution indistinguishable from the starting solution (glass beads should have no effect on removing the food coloring). The activated carbon should give clear or very lightly colored water. If the solution appears black, the food coloring has been successfully removed by chemical filtration, but the carbon dust escaped through the cotton ball plug at the bottom. In this case, filtered water can be discarded and experiment repeated with a new cup of colored water. Filtering through Brita granules should yield results very similar to filtering through granular activated carbon, with a solution that is near-colorless. The intensity of the color of filtered water can vary depending on how fast water was poured into the filter (faster pouring = more visible color). After the activity, have one group for each material share their results. Ask the students to summarize the results comparing the filters using glass beads, activated carbon, and Brita granules (if used). Volunteers can be asked to describe how their results differed from predictions (some students may be shy to do this as it reveals that they predictions were wrong or slightly off). For cleanup, the used materials inside the filters can be disposed in the trash. Glass beads can be rinsed, dried, and re-used as many times as desired. Activated carbon and Brita granules can be re-used at least 3 times.

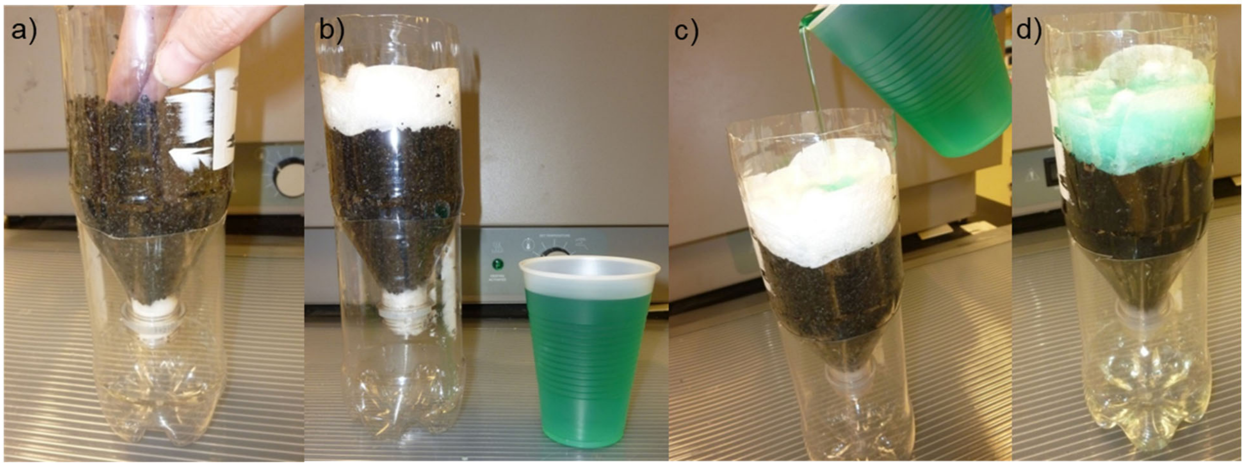

Figure 7: Chemical filtration activity: a) pack 1 cup of the selected filtration material into the plastic bottle arrangement used in the mechanical filtration activity (with a fresh cotton ball), b) cover the packed material with a paper towel and a 1 inch layer of cotton balls, c) slowly pour the colored water over the filter aiming to distribute the fluid evenly over the filtration materials, and d) do not let the liquid fill above the paper towel and cotton ball layer. Clarified water should drip through the filter gradually. The filtrate collected in the bottom of the bottle can be passed through the filter a second time to improve results.

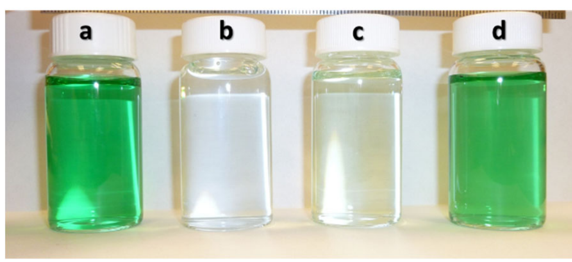

Figure 8: Chemical filtration results: a) original solution, which does not change after filtering through glass beads, b) 1 cup of original solution filtered through 1 cup of activated carbon, c) 1 cup of original solution filtered through 1 cup of Brita granules in a plastic bottle filter, and d) 1 cup of original solution filtered through Brita pitcher (~2/3 cup of granules in a filter cartridge).

<u>Explain Activity 2</u>: (10 minutes) The mixtures that did not separate using the filters in Activity 1 are called solutions. They consist of individual food coloring molecules surrounded by water molecules. Remind the students that some might have initially thought that water could not be made free of food coloring and be clear again. Explain that solutions can still be purified if the right methods are used as they had a chance to see in Activity 2. The activated carbon and the food dye molecules interact with each other in a special way (Figure 9), which makes the molecules stick to the surface. (How do you know? Because water comes out colorless.) This process is called chemical filtration. How about the glass beads? Do they interact with food dye

molecules? (No, because the liquid remains colored after passing through the layer of glass beads.) The Brita granules have some activated carbon that attracts food dye molecules, and some other beads that do not attract food dye molecules.

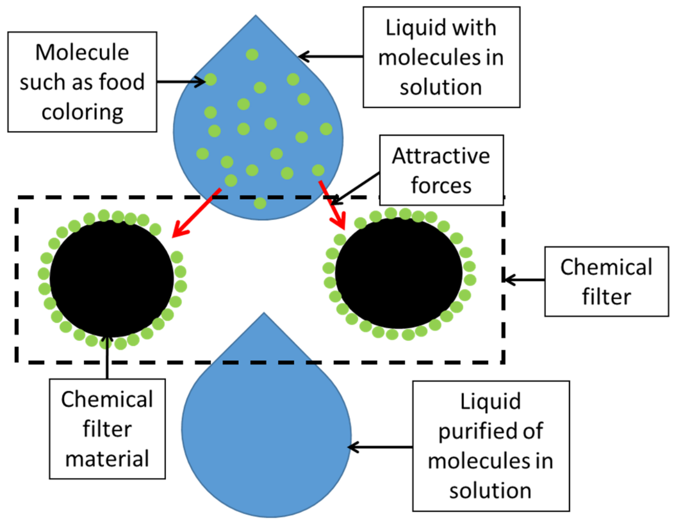

Figure 9: Explanation of chemical filtration (adsorption).

Elaborate: *(optional)* If time and resources allow, challenge more mature learners to design a plastic bottle chemical filter using Brita granules to give clear water. This activity may be done in groups or by individuals. The design portion could be completed as homework with the testing done in another class period or groups could brainstorm and test in a single class period. Demonstrate a Brita pitcher and contents of an opened cartridge to the students. Show them what the material looks like (Figure 6c). Do a demonstration: pour a cup of colored water into a Brita pitcher and show that very little color if any is removed from the water. Ask them whether they noticed differences between running water through the pitcher compared to their filtration devices (the most important factor is how fast water flows: it takes <1 min in the pitcher and 5-10 min in their plastic-bottle filters). Challenge the students create a filter with Brita granules that removes color almost as well or better than activated carbon they tested in Activity 2. Students can pick a variable to experiment with. Reasonable variables include thickness of the layer of Brita granules in filter, number of bottles with Brita granules, number of times to pour the water through the same filter, speed of pouring colored water into filter, adding activated carbon to Brita granules. Groups or individuals should compare results for multiple trials and designs to the controls of a Brita pitcher and 1 cup of activated carbon in the filter from Activity 2. Which variables made the biggest difference? Why? Any variable which increases the amount of Brita granules or the amount of time spent in contact with Brita granules should increase the time for attractions between the activated carbon in the granules and the food coloring molecules, helping to remove the coloring.

Evaluate: *(3-5 minutes)* At the end of the lesson, students can be assessed informally through summative evaluation using verbal, group questioning or formally using written responses to the questions below to determine if the students have met the learning objectives. Modifications can be made to this assessment to adapt it for a homework assignment or quiz for individual summative assessment.

Questions to Review and Assess Learning Objectives [Answers]

- What is filtration? [a way to remove solids or molecules from a liquid using a filter]
- What kind of filtration did you use to remove the cornmeal from the water in Activity 1? [mechanical]
- What is a pore? [a hole inside a filter or space between filter materials]
- How does pore size affect mechanical filtration? [only things smaller than the size of the pores can go through the filter]
- What kind of filtration did you use to remove the food coloring from the water? [chemical filtration]
- What quality determines if a filter will remove food coloring from water? [stickiness or interactions between the food coloring and the surface of the filter materials]
- How is mechanical filtration different from chemical filtration? [mechanical filtration relies on pore size being smaller than particle size, chemical filtration relies on interactions of dissolved molecules with surfaces of the pores]
- Name the type of filtration (mechanical or chemical) used in these common filters:
    - Coffee filter [mechanical]
    - Fish tank filter [mechanical and chemical]
    - Air conditioner filter [mechanical]
    - Kitchen sink water filter [chemical]

Experiences

The Filtration Fun lesson plan was developed in 2011 as part of a graduate course on science and engineering outreach. We did not formally assess the lesson plan through a pedagogical experiment as most of the venues for teaching it were at events managed by other organizations. The logistics made it challenging to acquire parental permissions for studying minors. We did obtain some of data from assessments from the partner programs after we used the lessons, however the feedback was vague and often limited as part of a survey about a larger camp or event. The feedback regarding calls to improve engagement level and interactivity have been incorporated into the lesson presented here. Additionally, the files were peer-reviewed by science and engineering faculty, curriculum and instruction faculty, and middle school teachers. The lesson activities were tested in middle school classrooms and an after school program in a Boys & Girls Club, with observations and feedback from course instructors and middle school teachers. The plan was showcased at a professional development workshop for K-12 science teachers, where more teacher feedback was incorporated. Unfortunately, after we graduated, the course and network of local educators was disbanded, so no longitudinal data are available to determine if any of those teachers from the development time frame have incorporated this lesson into their classroom activities. We aim to foster this in the future by disseminating this lesson plan. Activities from the lesson plan have been used separately in several outreach activities since 2011 including multiple Girl Scout events for 6th-12th graders in Massachusetts and a summer camp at Oklahoma State University for 4th-8th graders and their grandparents called Grandparent University, with feedback from some of these programs' participants. In the briefest type of in-person outreach interactions (1-5 min) at a science festival booth, the hop-on-one-foot activity can be used if space allows, and the mechanical and/or chemical filtration activities can be prepared in advance and tested repeatedly by participants. These have been successfully paired with a slideshow of photos from an Engineers Without Borders trip to deploy water filtration devices in another country. For one-hour sessions with middle school students, the mechanical filtration experiment and the hop-on-one-foot activity are used in full, and then the instructor demonstrates the chemical filtration experiment. The full design challenge and comparing various materials for chemical filtration are more appropriate for high school students. We have used this lesson as a basis for a workshop in a large Girl Scout event called Changing the World through STEM hosted by the Girl Scouts of Eastern Massachusetts Council. There, we incorporated more background information about chemical engineering and discussion of technology that engineers use to purify the world's drinking water supplies using chemical engineering principles. We have also adapted this lesson as an introduction to filtration as a key process that our bodies use to remove liquid waste via the kidneys. This biomedical engineering lesson included discussions of filtration research for improving technologies for dialysis and artificial kidneys. We have interpreted our invitations to participate year after year in the Changing the World through STEM event and the Grandparent University camp as positive feedback on the effectiveness of the program in engaging participants in the filtration topics.

Our lesson plan materials including background descriptions for science teachers and detailed set-up instructions are available online[16].

List of files

1. Filtration Fun lesson plan written for science teachers
2. Classroom slides: Presentation for classroom use for full Filtration Fun lesson plan that can also be printed as handouts/worksheets
3. Outreach workshop slides: Presentation for use in informal STEM outreach setting for Clean Water through Chemical Engineering
4. Teachers Notes presentation slides
    a. Mechanical filtration background info (separation of cornmeal from water)
    b. Chemical filtration background info (removal of food coloring from water)
    c. Mechanical filtration experiment setup tutorial
    d. Chemical filtration experiment setup tutorial

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