Dyes and Chemical Bonding

Introduction

The affinity of a dye for a fabric depends on the chemical structures of the dye and fabric molecules and on the interactions between them. Chemical bonding thus plays an important role in how and why dyes work.

Concepts

- Polar vs. nonpolar bonds
- Ionic bonds
- Hydrogen bonding

Background

The chemical structures of six common fabrics are shown in Figure 1. Cotton and wool are natural fibers while acrylic, polyester, and nylon are synthetic. Acetate, also called cellulose acetate, is prepared by chemical modification of natural cellulose. All of the fabrics are polymers. These are high-molecular weight, long-chain molecules made up of multiple repeating units. The structures of the repeating units are enclosed in brackets.

Wool is a protein made up of amino acid repeating units. Many amino acids have acidic or basic side chains that are ionized (charged). The presence of charged groups provides excellent binding sites for dye molecules, many of which are also charged. Cotton is a polysaccharide composed of glucose units. The presence of three polar –OH groups per glucose unit provides multiple sites for hydrogen bonding to ionic and polar groups in dye molecules. Acetate is cellulose in which some of the –OH groups have been replaced by acetate groups (–$OCOCH_3$). The presence of acetate side chains makes acetate softer and easier to work with than cotton but also provides fewer binding sites for dye molecules.

Nylon was the first completely synthetic polymer fiber. It is made up of hydrocarbon repeating units joined together by highly polar amide (–CONH–) functional groups, which provide sites for hydrogen bonding to dye molecules. Polyester contains ester
(–COO–) functional groups, while acrylic fiber is poly(acrylonitrile), consisting of nitrile (–C≡N) functional groups.

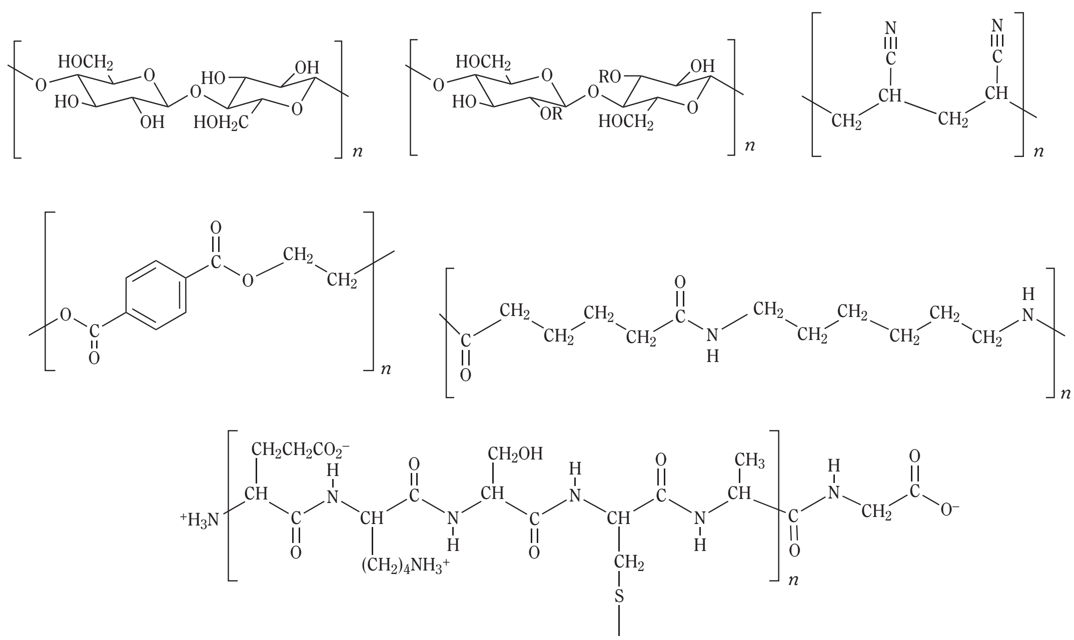


Figure 1. Chemical Structures of Fabric Molecules.

Direct dyes are charged, water-soluble organic compounds that bind to ionic and polar sites on fabric molecules. Direct dye molecules contain both positively and negatively charged groups and are easily adsorbed by fabrics in aqueous solution. The purpose of this activity is to investigate the interaction of direct dyes with different fabrics. The direct dyes are methyl orange, malachite green, and crystal violet. See Figure 2 for the structures of the dye molecules. The dyes will be tested on a multifiber test fabric that contains strips of six different fibers—wool, acrylic, polyester, nylon, cotton, and acetate (Figure 3).

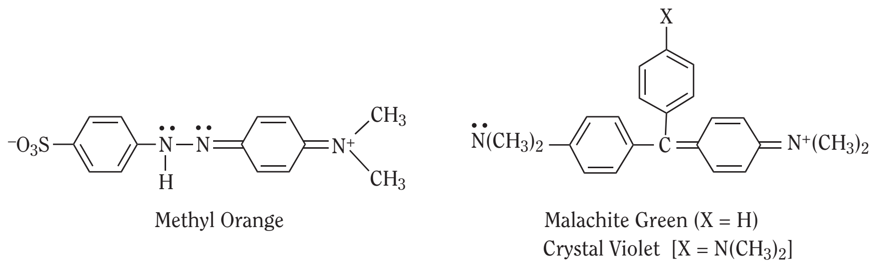


Figure 2. Chemical Structures of Dye Molecules.

Hypothesis

1. Identify the groups in the structure of methyl orange that will bind to ionic and polar sites in a fabric.
2. Complete the following "If/then" hypothesis.

   "If a fabric contains more ionic and polar groups in its structure, then the intensity of the dye color due to methyl orange should (increase/decrease), because ____ ________________.
3. Using this hypothesis, predict the relative color intensity that will be produced by methyl orange on the fibers in the multi-fiber test fabric. Rank the fabrics from 1 = lightest color to 6 = darkest color.

Wool	Acrylic	Polyester	Nylon	Cotton	Acetate

Figure 3. Composition of the Multifiber Test Fabric.

Materials (for each group of students)

Distilled water and wash bottle
Forceps or tongs
Multifiber test fabric, 6 cm
Pencil
Scissors
Stirring rods
Weighing dishes, large, 3
Paper towels
Dye baths (may be shared)
Crystal violet
Malachite green
Methyl orange
Hot plates, 3

Preparation of Dye Baths *(for a class of 30 students working in pairs)*

Prepare 600 mL of each dye solution and divide or set out in three 200-mL dye baths, which may be used by several classes throughout the day.

Crystal Violet: Dissolve 0.3 g of crystal violet in 600 mL of distilled or deionized water. Place a boiling stone in the dye solution and heat to near boiling on a hot plate.

Malachite Green: Dissolve 0.3 g of malachite green in 600 mL of distilled or deionized water. Place a boiling stone in the dye solution and heat to near boiling on a hot plate.

Methyl Orange: Dissolve 2.0 g of methyl orange in 600 mL of distilled or deionized water. Add 3 g of anhydrous sodium sulfate (Na_2SO_4) and 6–8 drops of concentrated sulfuric acid. Place a boiling stone in the dye solution and heat to near boiling on a hot plate.

Safety Precautions

All of the dyes are strong stains and will stain skin and clothing. Methyl orange, crystal violet, and malachite green are toxic by ingestion. The dye baths are very hot, near boiling. Exercise care to avoid scalding and skin burns. Avoid contact of all chemicals with eyes and skin. Wear chemical splash goggles and chemical-resistant gloves and apron. Wash hands thoroughly with soap and water before leaving the lab. Please consult current Safety Data Sheets for additional information.

Procedure

1. Cut the multifiber test fabric crosswise to obtain three 2-cm strips with all six fabrics on each swatch (Figure 3). Note that the wool fabric is cream-colored, not white. Use a pencil to mark the wool ends with a "W." Label the strips with your initials as well.
2. Label three weighing dishes with the names of the dyes to be tested.
3. All of the dyes are strong stains. Avoid getting any dye solution on your skin, clothes or books. To avoid contamination, rinse tongs or forceps with water before inserting them into a dye bath.
4. Fold a multifiber test strip in half. Using forceps or tongs, immerse the test strip into the *crystal violet* dye bath. *Caution:* The dye baths are very hot. Exercise care to avoid scalding or skin burns.
5. After 5–10 minutes, remove the dyed test strip from the bath using forceps. Hold the fabric above the dye bath for a few minutes and allow the excess dye solution to drain back into the dye bath.
6. Pat the test strip with paper towels and rinse the dyed test strip under running water from the faucet or a wash bottle. Continue rinsing the test strip until all of the excess dye has been removed and the rinse water is colorless.
7. Place the rinsed test strip in the appropriately labeled weighing dish and allow it to air dry.
8. Repeat steps 4–7 with new test strips in the *malachite green* and *methyl orange* dye baths.
9. When the fabrics are dry, record the color produced by each direct dye on each type of fabric.

Discussion Questions *(Use a separate sheet of paper to answer the following questions.)*

1. Describe the colors produced by methyl orange on the different fabrics in the multifiber test fabric. Compare the results with the relative color intensities predicted in the hypothesis. Explain any differences between the predicted and actual results.
2. Compare the general ease of dyeing the six different fabrics in the multifiber test fabric. Which fabric(s) consistently developed the most intense colors? Which fabric was the most difficult to dye?
3. *Consult Figure 1:* What feature stands out as unique in the structure of the fabric that was the easiest to dye? What feature stands out as unique in the structure of the fabric that was hardest to dye?
4. Compare the relative color intensities produced by crystal violet and malachite green on different fabrics. Are the color *patterns* (from lightest to darkest) similar for these two dyes? Explain.

Disposal

Consult your current *Flinn Scientific Catalog/Reference Manual* for general guidelines and specific procedures, and review all federal, state and local regulations that may apply, before proceeding. The dye solutions may be washed down the drain with plenty of excess water according to Flinn Suggested Disposal Method #26b.

Connecting to the National Standards

This laboratory activity relates to the following National Science Education Standards (1996):

Unifying Concepts and Processes: Grades K–12

Evidence, models, and explanation
Constancy, change, and measurement
Form and function

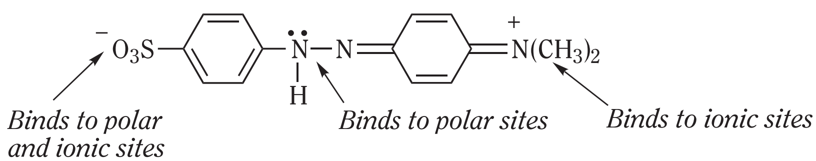
Content Standards: Grades 9–12

Content Standard A: Science as Inquiry
Content Standard B: Physical Science, structure of atoms, structure and properties of matter, chemical reactions, motions and forces, conservation of energy and increase in disorder, interactions of energy and matter
Content Standard G: History and Nature of Science, science as a human endeavor, nature of scientific knowledge, historical perspectives

Lab Hints

- Place lots of paper towels or absorbent lab mats all around the dye baths. This will help keep the room clean. Instruct students to store books, bags, and other personal items away from the lab area to avoid staining them.
- The multifiber test fabric (Catalog No. AP6135) is fairly expensive but the color patterns are beautiful and intriguing. To save money, the teacher may wish to dye multifiber test strips as part of a demonstration and have students bring fabrics of their own choosing to dye during the experiment. Suitable fabrics from home include cotton T-shirts, acrylic socks or yarn, polyester sheets, etc. Scavenge fabric stores for inexpensive bolts of white cloth (read the labels!). Pure (100%) white cotton, polyester, acetate, and nylon are easy to find and inexpensive. Wash fabrics before dyeing to remove sizing and other fabric finishes.
- The structures of fabric and dye molecules may be intimidating. Focus on ionic and polar groups in the structures—these are the groups that will influence the dyeability of a fabric.
- This lab offers a perfect opportunity to highlight consumer applicatons of chemistry. Research the fascinating early history of natural dyes and dyeing—there are some great stories. For a well-reviewed book about the impact of mauve on the history and development of science, see *Mauve: How One Man Invented a Color that Changed the World*, by Simon Garfield.

Sample Hypothesis *(Student answers will vary.)*

1. 

2. *If a fabric contains more ionic and polar groups in its structure, then the intensity of the dye color due to methyl orange should increase, because there will be more sites on the fabric for the dye molecules to bind to.*

3.

Wool	Acrylic	Polyester	Nylon	Cotton	Acetate
6	2	1	4	5	3

Sample Results *(Student data will vary.)*

	Wool	Acrylic	Polyester	Nylon	Cotton	Acetate
Methyl Orange	Red	White	Pale yellow	Orange	Light yellow	Yellow
Malachite Green	Dark green	Blue-green	Pale green	Light green	Blue-green	Turquoise
Crystal Violet	Dark blue	Periwinkle	Light blue	Blue	Royal blue	Blue

Answers to Discussion Questions *(Student answers will vary.)*

1. *Observed color intensity: Wool > nylon > acetate > cotton > polyester > acrylic*

   The color of methyl orange ranged from dark red-orange on wool and bright orange on nylon to essentially colorless (white) on acrylic. Acetate was dyed lemon yellow, while cotton and polyester were light yellow and pale yellow, respectively. Student predictions will vary. Most should predict that wool will show the greatest affinity for the dye, and thus the most intense color with methyl orange. The results for nylon may be a surprise, since there are no charged groups shown in the structure of nylon. Both nylon and wool contain amide-linking groups in their repeating units—the polar amide groups may interact with the dye via hydrogen bonding.

2. *Wool consistently developed the most intense colors with all of the dyes. Nylon, cotton, and acetate were also relatively easy to dye. Polyester was the most difficult fabric to dye.*

3. *Wool contains many charged groups in its structure. None of the other fabrics show any charged groups in their normal repeating units. Polyester is unique in that it appears to be the least polar of all the fabrics. Polyester has no –X–H (where X = O or N) groups capable of forming hydrogen bonds with electron donor sites in dye molecules.* ***Note to teachers:*** *Acrylic fiber is similar to polyester in that it appears to lack polar groups capable of hydrogen bonding to electron donor sites in dye molecules. The dyeability of acrylic is improved commercially by incorporating small amounts of charged monomers into the growing polymer.*

4. *Crystal violet and malachite green have similar structures and produced similar color patterns with the six fabrics in the multifiber test fabric. The observed color intensity produced by crystal violet and malachite green was:*

   Wool > cotton, acrylic, and acetate > nylon >> polyester.

Materials for *Color of Chemistry* are available from Flinn Scientific, Inc.

Catalog No.	Description
AP6135	Multi-Fiber Test Fabric, 1 yard
C0129	Crystal Violet, 5 g
M0129	Malachite Green Oxalate, 10 g
M0076	Methyl Orange, 25 g

Consult your *Flinn Scientific Catalog/Reference Manual* for current prices.