

The Color of Chemistry

Dyes, Dyeing, and Chemical Bonding

Introduction

The art of dyeing dates back thousands of years to the use of natural dyes extracted from plants and animals. Some dyes, such as Tyrian purple obtained from shellfish, were so rare that only emperors and kings could afford to wear purple—hence the term “royal purple.” The modern dye industry started 150 years ago with the discovery of “mauve,” the first synthetic dye. Since then, thousands of dyes have been developed to work with all types of fabrics.

Concepts

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

Background

Dyes are organic compounds that can be used to impart bright, permanent colors to fabrics. The affinity of a dye for a fabric depends on the chemical structure 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.

The chemical structures of six common fabrics—wool, acrylic, polyester, nylon, cotton, and acetate—are shown in Figure 1. Cotton and wool are natural fibers obtained from plants and animals, while acrylic, polyester, and nylon are synthetic fibers made from petrochemicals. Acetate, also called cellulose acetate, is prepared by chemical modification of natural cellulose. All of the fabrics, whether natural or synthetic, are polymers. These are high molecular weight, long chain molecules made up of multiple repeating units of small molecules. The structures of the repeating units are enclosed in brackets in Figure 1. The number of repeating units (n) varies depending on the fiber and how it is prepared.

Wool is a protein, a naturally occurring polymer made up of amino acid repeating units. Many of the amino acid units have acidic or basic side chains that are ionized (charged). The presence of many charged groups in the structure of wool provides excellent binding sites for dye molecules, most of which are also charged. Cotton is a polysaccharide composed of glucose units attached to one other in a very rigid structure. The presence of three polar hydroxyl ($-OH$) groups per glucose repeating 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 Acetate is cellulose in which some of the $-OH$ groups have been replaced by acetate groups ($-OCOCH_3$).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 a polyamide, made up of hydrocarbon repeating units joined together by highly polar amide ($-CONH-$) functional groups. The amide groups provide sites for hydrogen bonding to dye molecules. The repeating units in polyester are joined together by ester ($-COO-$) functional groups. Finally, acrylic fiber is poly(acrylonitrile). Each repeating unit contains one nitrile ($-C\equiv N$) functional group.

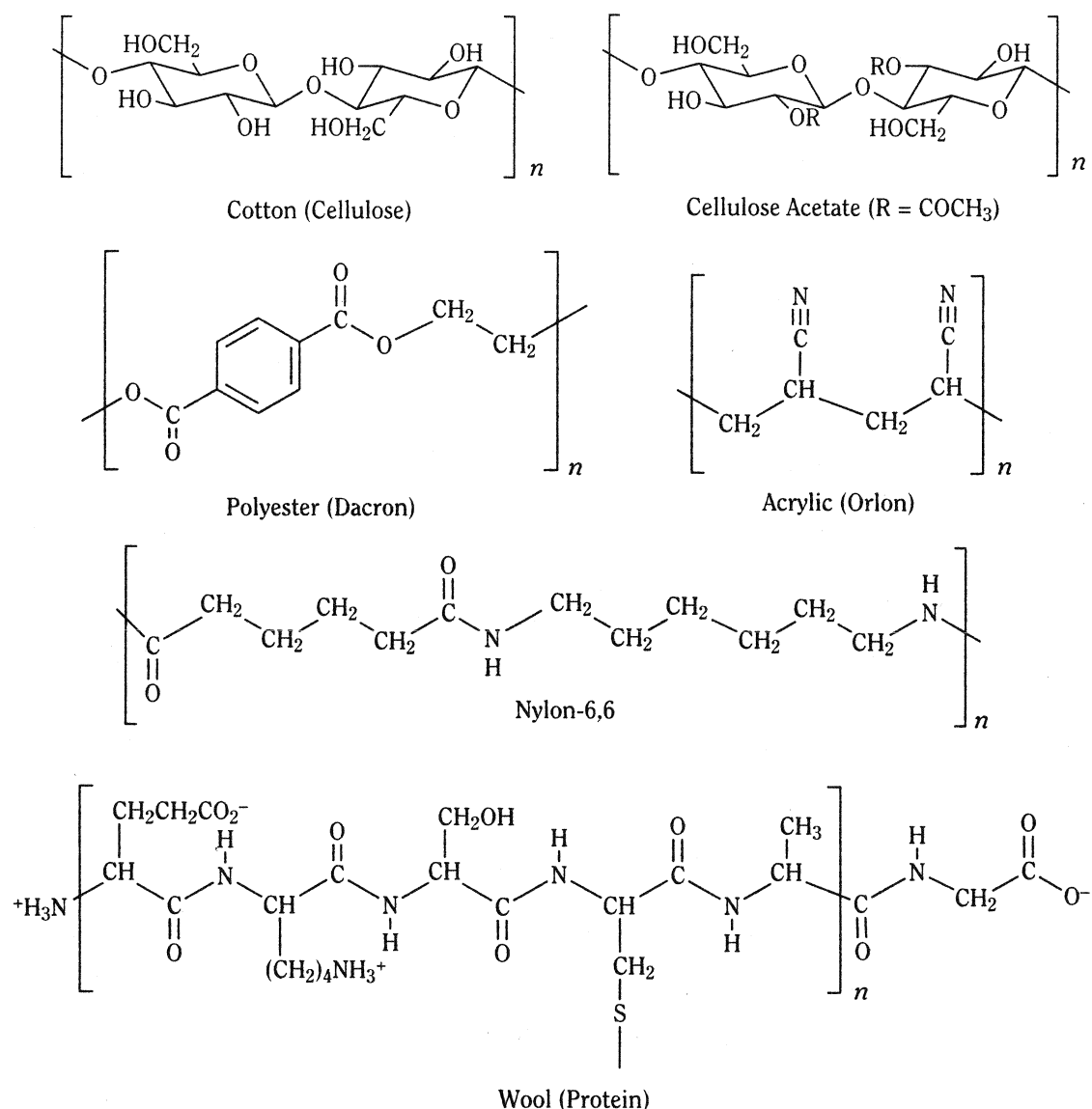


Figure 1. Chemical Structures of Fabric Molecules.

Dyes are classified based on both the structure of the dye and the way in which the dye is applied to the fabric.

- *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. Simple salts such as sodium chloride and sodium sulfate may be added to the solution to increase the concentration of dye molecules on the fiber.
- *Substantive dyes* interact with fabrics primarily via hydrogen bonding between electron donating nitrogen atoms ($-N:$) in the dye and polar $-OH$ or $-CONH-$ groups in the fabric.

- The ability of a dye to bond to a fabric may be improved by using an additive called a mordant. *Mordant dyes* are used in combination with salts of metal ions, typically aluminum, chromium, iron, and tin. The metal ions adhere to the fabric and serve as points of attachment for the dye molecules.
- *Vat dyes* are colored organic compounds that do not dissolve in water. Vat dyes can be reduced chemically to form colorless, water-soluble derivatives. Upon exposure to air the colorless form of a vat dye is oxidized back to the colored form. Vat dyes are introduced to the fabric in their colorless, reduced form and then “developed” by exposing the fabric with the ingrained dye to air. The most famous vat dye is indigo, which is used to dye blue jeans.

Experiment Overview

The purpose of this activity is to investigate the interaction of dyes with different fabrics. The dyes include methyl orange, malachite green, and crystal violet (direct dyes); congo red (a substantive dye); alizarin (a mordant dye); and indigo (a vat dye). 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).

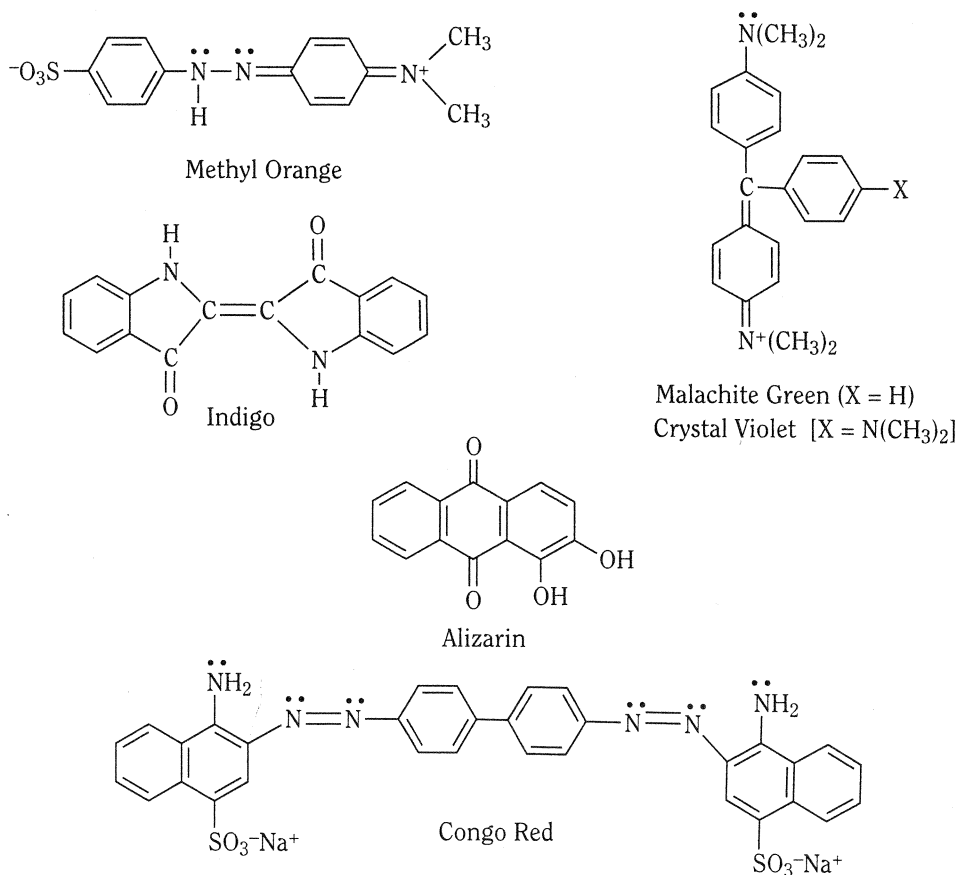


Figure 2. Chemical Structures of Dye Molecules.

Pre-Lab Questions

1. Redraw the structure of methyl orange (Figure 2), and identify the groups in the dye that will bind to ionic and polar sites in a fabric.
2. Complete the following “If/then” hypothesis to explain how the structure of a fabric will influence the relative color intensity produced by methyl orange.

“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 six fibers in the multifiber 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.

4. Form a working group with two or three other students. Read the entire *Procedure* and the recommended *Safety Precautions*. This is a cooperative lab activity—decide how you will divide up the lab work and write out an action plan. You will not have time to complete the activity if one of the partners does all the work.

Materials

Distilled water and wash bottle
 Forceps or tongs
 Multifiber test fabric, 14 cm
 Pencil
 Permanent marker
 Scissors
 Stirring rods
 Weighing dishes, large, 7
 Paper towels

Dye baths

Alizarin red
 Congo red
 Crystal violet
 Indigo
 Malachite green
 Methyl orange

Mordant bath

Aluminum potassium sulfate, $\text{AlK}(\text{SO}_4)_2$

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 and irritating to body tissue. Alizarin red is a body tissue irritant. 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.

Procedure

1. Cut the multifiber test fabric crosswise to obtain seven 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 six weighing dishes with the names of the dyes to be tested (see the “Dye baths” in the *Materials* section). Label a seventh weighing dish “Alizarin + Alum.”
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.

Part A. Direct Dyes

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 dye color produced by each direct dye on each type of fabric. See the *Data Table*.
10. (*Optional*) Test whether the dyed fabrics are colorfast: Cut the dyed test strips in half to obtain two identical 1-cm strips of dyed multifiber fabrics. Wash one test strip with soap and water and rinse well. Keep the other strip as a control. Record any color changes or observations on the data sheet.

Part B. Substantive Dye

11. Repeat steps 4–7 and 9–10 with a new multifiber test strip in the *congo red* dye bath.

Part C. Mordant Dye

12. Use a pencil to write “Alum” on the side (selvage) of a test strip.
13. Using forceps or tongs, immerse the “alum”-labeled test strip into the boiling *mordant* bath (aluminum potassium sulfate).
14. After 15–20 minutes, remove the test strip from the mordant bath. Allow the fabric to cool slightly and then wring it out over the bath to remove excess liquid.

15. Immerse both the mordanted test strip and an untreated test strip in the *alizarin* dye bath.
16. After 5–10 minutes, remove the test strips from the dye bath. Rinse and dry the test strips as described in Part A, steps 5–7.
17. Record the colors produced by alizarin on both the mordanted and untreated test strips.

Part D. Vat Dye

18. Immerse a test strip in the *indigo* dye bath and boil gently for 5–10 minutes.
19. Using forceps or tongs, remove the dyed test strip from the dye bath and rinse well with water.
20. Allow the test strip to air dry, then record the colors produced by indigo dyeing on each type of fabric.

Name: _____

Class/Lab Period: _____

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Data Table

	Wool	Acrylic	Polyester	Nylon	Cotton	Acetate
Methyl Orange						
Malachite Green						
Crystal Violet						
Congo Red						
Alizarin						
Alizarin + Alum						
Indigo						
	Wool	Acrylic	Polyester	Nylon	Cotton	Acetate

(Optional) Use this space to write down any observations concerning the colorfastness of the dyes.

Post-Lab 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 *Pre-Lab Questions*. 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, regardless of the type of dye used? 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. *Consult Figure 2:* Which two dyes have very similar structures? Compare the relative color intensities produced by these dyes on the different fabrics in the multifiber test fabric. Are the color *patterns* (from lightest to darkest) similar for these two dyes? Explain.
5. Compare the color *patterns* produced on the different types of fabrics by methyl orange (a direct dye) and congo red (a substantive dye). Suggest a possible reason for any differences based on the chemical bonding interactions of direct versus substantive dyes (see the *Background* section).
6. Show by means of a diagram one hydrogen bond that might form between a glucose unit in cotton and congo red. *Hint:* Hydrogen bonds have the general form $-X-H \cdots :Y$, where X and Y are highly electronegative atoms such as N, O, F, and Y has an unshared pair of electrons.
7. Compare the colors produced by alizarin on the untreated and mordanted test strips. What is the principal advantage of using a mordant? What fabric was almost impossible to dye except with a mordant?