Low-Cost Laboratory Adaptations for Precollege Students Who Are Blind or Visually Impaired

Cary A. Supalo* and Thomas E. Mallouk
Department of Chemistry, Pennsylvania State University, University Park, PA 16802; **cas380@psu.edu*

Lillian Rankel
Pennington, NJ 08534

Christeallia Amorosi
State College, PA 16801

Cameala M. Graybill
New Providence, PA 17560

Students who are blind or have low vision are entering mainstream science classrooms at a greater rate than in decades past, requiring teachers to devise strategies for making their lessons more accessible. Because much of chemistry is visual in nature, it is difficult to provide these students with a laboratory experience that is comparable to that of their sighted peers. A number of assistive technologies, such as talking balances and thermometers, are already available. However, several challenges still exist, such as the accurate measurement of volumes, and the observation of color changes and precipitate formation, although these too may be addressed *(1–3).* These inexpensive laboratory adaptations increase accessibility to experiments and classroom exercises for students who are blind or visually impaired, increasing the likelihood that they will continue to study science at the postsecondary level and ultimately pursue careers in science, technology, engineering, or mathematics professions *(4).*

Several computer-based and tactile adaptive technologies for chemistry laboratories have been developed over the past three decades. In the 1980s, Lunney and Morrison interfaced PCs with speech output technology, creating a device that spoke pH readings, performed titrations, and analyzed gas chromatographic data *(5).* They also wrote software that interfaced with pH electrodes, the Spectronic 20, IR spectrophotometers, and a piston buret. More recent work by Wohlers and colleagues *(6)* interfaced the Braille ‘n Speak, a talking portable note taking tool, with common laboratory equipment, including balances, UV–visible and FTIR spectrophotometers. In its “speech box”’ mode, the Braille ‘n Speak receives an ASCII feed from another device and then speaks the data value.

Kumar et al. have outlined special considerations for blind and low vision students in the laboratory *(7).* The importance of familiarization with safety protocols is discussed, as is the use of raised-line drawings for graphics and balances for determining volumetric measurements. When used in conjunction with a reaction vessel, a white background provides high contrast and helps students with low vision see reactions as they occur. Acid–base titration experiments are possible by connecting a colorimeter to a PC, which can then identify color changes and end points.

A paper by Smith *(8)* discusses several low-cost classroom tools for students who are blind. She describes a periodic table constructed with Braille-labeled wood blocks. An extension of this device is the use of a metallic board and magnets attached to shapes that represent different elements. These elements are then used to illustrate Lewis dot structures in a tactile manner. A companion paper by Tombaugh *(9)* further discusses the importance of tactile drawings made with a tracing wheel and Braille paper, producing raised lines that students can then feel. Hot glue can also be used to make low-cost raised line drawings. The Cranmer abacus, viewed in the blind community as the equivalent of scratch-paper and pencil, can also be used as a tactile aid in calculations *(10).* It allows the student to directly manipulate numbers in calculations, rather than use a talking calculator. Braille rulers and raised-line marked rulers can be used for measurements of length, and a balance can be used to measure volumes gravimetrically. All of these tools are affordable and are easily adapted by teachers of students who are blind or visually impaired.

Volumetric Measurements

Lawrence Hall of Science has recently developed several tools for making volumetric measurements. The first is a disposable plastic syringe with markings calibrated to volumes notched onto the plastic pull tab, providing tactile markers. Braille labels are used to identify the calibration volumes (Figure 1A).

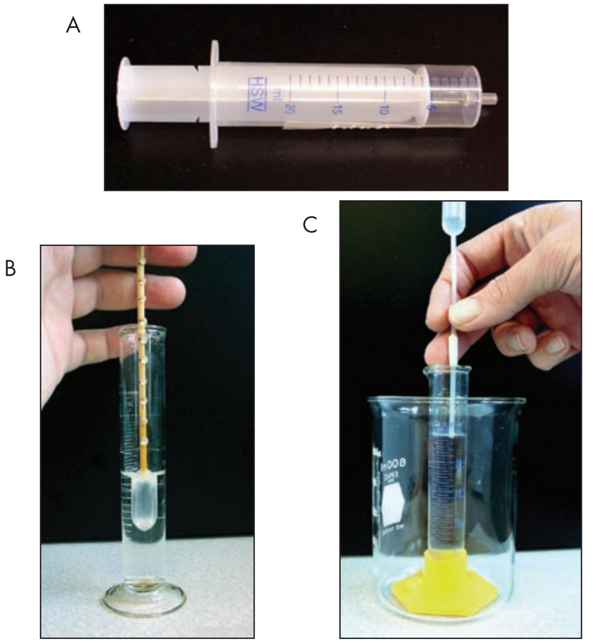

Figure 1. Examples of adaptive equipment, including: (A) a notched plastic syringe; (B) a floating volumetric measuring device; and (C) a graduated cylinder and pipette.

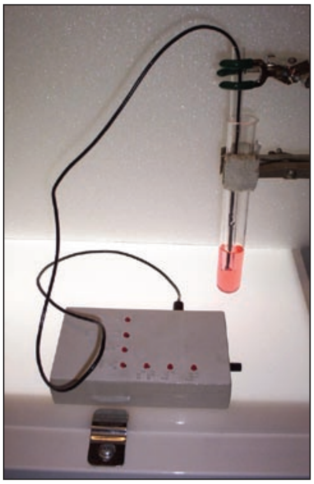

Figure 2. Real-time submersible audible light sensor in use.

Another tool developed for measurements in a graduated cylinder is a flotation device. A lightweight rod is fitted with a hollow plastic tip; then, using a hot glue gun, the rod is marked with raised dots at regular intervals corresponding to volumes (Figure 1B) *(11)*.

Plastic graduated cylinders of different capacities are also appropriate for measuring specific amounts of liquids, albeit in an unusual fashion. A graduated cylinder is filled to the top with solution; liquid is then drawn out using a plastic transfer pipette, calibrated to the specified cylinder, until the cylinder contains the desired volume. A piece of tape on the pipette stem marks how far into the cylinder it should be inserted to remove a given volume of liquid. For stability and convenience, ready-for-use graduated cylinders can be placed in a beaker, together with taped and marked pipette(s) for the cylinder. Placing the graduated cylinder inside a beaker helps to steady it and also minimizes the impact of spills (Figure 1C).

Detection of Light Intensity and Color Changes

Many laboratory experiments involve observations of visible changes in liquids, such as the color change of an acid–base indicator or the formation of a precipitate. In order for students who are blind or have low vision to monitor these chemical reactions in real time, we developed a submersible audible light sensor (SALS) *(12)*. This device contains a photocell in the tip of a glass wand wired to a tone output device. Changes in light intensity detected by the sensor result in changes in the pitch of the output tone. Higher pitch indicates that the sample is more transparent. A change in color or formation of a precipitate will usually result in a change in light transmittance, which can be picked up by the sensor. The light sensor is inserted into the solution and the user manipulates the control buttons to listen, store, or to compare a current pitch to a stored reference pitch, as shown in Figure 2.

The SALS device was tested with the iodine clock reaction, an experiment in which abrupt solution color changes—from colorless to blue to black—are observed, followed by formation of a black precipitate. In the Prentice Hall Laboratory Manual *(13)*, the clock reaction is used to teach the relationship between concentrations of reactants and reaction rates. In separate runs, the output pitches resulting from specific colors were consistent within approximately one musical whole-step. The SALS device was also tested with the acid–base indicators phenolphthalein and thymolphthalein to observe pH changes. Phenolphthalein is colorless in acid and pink in base, whereas thymolphthalein is colorless in acid and blue in base. Because these indicators display rather faint color changes at the concentrations ordinarily used in acid–base titrations, concentrations were increased for use with the SALS device. Each titration used 40 drops of acid–base indicator (approximately 0.7 mL of 0.016 M thymolphthalein in 95% ethanol) in 70 mL of an aqueous solution that contained 2.9% vinegar (approximately 0.024 M acetic acid). This solution was titrated with 0.1 N NaOH (17–18 mL). With the SALS sensor, the deep blue color change at the equivalence point was read as a change in pitch of approximately one-half octave.

Balances for Determining Mass

A single pan triple-beam balance (Ohaus 8274), with a capacity of 311 g and readability of 0.01 g, can be used with a slight modification. The 200 g, 100 g, 10 g, and 1g beams of this balance are notched. This causes a clicking noise as the weight slides over the notched beam. Massing can be accomplished by counting the notch clicks. The smooth 0.1 g beam can be read by counting pieces of tape placed at each 0.1 g intervals, and the 0.01 g position can be estimated. As the mass of the tape will vary depending on the size of the pieces, the tape should be weighed and compensated for in mass calculations. Single pan balances can be purchased from laboratory suppliers for about $175. A triple-beam balance with a capacity of 500 g and an accuracy of 0.1 g can be modified with tape on the 0.1 g beam in the same manner, and costs about $110 *(7, 14)*.

Magnetic Board for Lewis Dot Structures, Aufbau Diagrams, and Electron Configurations

A magnetic dry-erase writing board with magnetic Braille-labeled or cut-out letter element symbols facilitates exercises on the electronic structure of elements and compounds. Movable symbols representing elements and electrons are made with peel-and-stick type business card magnets and craft peel-and-stick foam sheets, which are easily cut with scissors. These can illustrate Lewis dot structures, Aufbau orbital energy diagrams, and electron configurations in different ways. Combining these three facets of electronic structure into one activity enables students to experience basic quantum principles and chemical bonding on several levels. A student may begin by choosing a metal and nonmetallic element (for example K and F) from the magnetic element symbols. Magnetic "electrons" with an arrow shape are cut from plastic magnetic strips and coated with a rough foam for metal electrons and smooth foam for non-metal electrons. These tactile electrons take the place of the "x" and "o" notation often used to show the distribution of electrons. The electrons are placed around the K and F to show their initial Lewis dot structures. When K reacts with F to form an ionic compound, the K electron moves over to the F; a magnetic +1 is placed by the K cation and a −1 is placed by the F anion to show the charge that results from the transfer of the electron.

As shown in Figure 3, a Braille-labeled page detailing the different energy levels in raised-line format shows the electronic structure of an atom. The magnet board can be used to illustrate electron transfer reaction from a metal to a nonmetal. Textured magnetic electrons are placed in the appropriate energy levels in Aufbau order, following the Pauli exclusion principle and Hund's rule. Valence electrons are then transferred from the metal orbitals to the nonmetal orbitals. Finally, Braille tiles can write the electronic configuration of the metal and nonmetal and then allow adjustments to the electronic configurations, reflecting changes resulting from ionic bonding. When ionic bonds are formed between cations and anions, the student physically moves the magnets representing the electrons from the cation to the anion. This moving process illustrates the idea that valence electrons are not shared in the limit of completely ionic bonding.

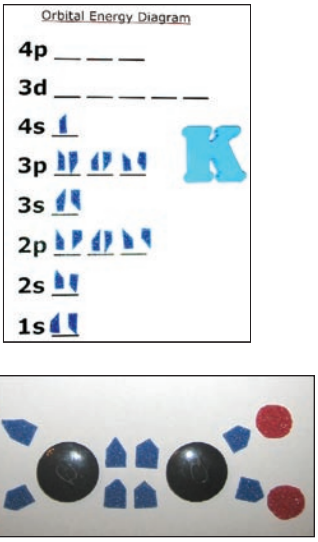

Figure 3. Magnet boards showing the Aufbau orbital filling for potassium (top) and the carbon-atom electrons for covalent bonding in ethene (bottom).

Differentiating Paramagnetic and Diamagnetic Ionic Compounds

Paramagnetic ions contain unpaired electrons and are attracted to the field of a strong magnet, whereas diamagnetic compounds (with no unpaired electrons) are not attracted to a magnet. Flinn Scientific sells a "Paramagnetic Metal Ions" kit for about \$30 that contains a neodymium iron boride magnet. The magnet deflects small V-shaped chambers containing paramagnetic or diamagnetic metal salts *(3)*. When the chambers contain $MnSO_4$ (which has five unpaired electrons in the Mn 3d orbitals, i.e., $3d^5$) or $CuSO_4$ (which is $3d^9$ and contains one unpaired electron), the sample is drawn into the magnetic field. However, with $CaSO_4$ (no d electrons) or $ZnSO_4$ (which is $3d^{10}$ and has no unpaired electrons), the samples are not attracted to the magnet. Braille-labeling the samples easily adapts them for blind students, and complements the tactile learning activity on electronic structure.

Covalent Bonding and the Octet Rule

Using a magnetic dry-erase writing board with large round carbon symbols, other element symbols (O, N, Cl, S, etc.), and small rough foam circles for hydrogen can facilitate the study of covalent bonding. The atoms and their valence electrons are placed in a way that shows the sharing of electrons. The octet rule is illustrated by electron placement in bonds and nonbonded electron pairs, and doubly- and triply-bonded molecules can be made. It is also possible to illustrate exceptions to the octet rule, as in electron-deficient compounds such as BF_3 or hypervalent compounds such PF_5. In these cases, the exceptions are shown as fewer than or more than eight tactile electrons, respectively, around the central atom.

Valence Shell Electron Pair Repulsion Theory Models

Learning the geometry of molecules containing nonbonding electron pairs is facilitated by tactile three-dimensional models. A model kit sold by Flinn Scientific for about \$50 is very helpful for teaching these aspects of valence shell electron pair repulsion (VSEPR) theory. Lone electron pairs (in the form of spherical shapes), atoms, and bonds are easy to assemble. The atoms are identified by size or Braille labels. Students feel the molecular models, thereby learning the geometry and bond angles. For example, water is a bent molecule with two nonbonding electron pairs. The dihedral angle between the plane of the nonbonding electron pairs on the oxygen atom and the plane of H–O–H nuclei is 90°. The H–O–H angle (104°) can be measured by using a Braille protractor to illustrate the approximately tetrahedral arrangement of bonds and electron pairs around the oxygen atom. Other models (including NH_3, SF_4, XeF_4, ICl_5, and HCl) can demonstrate the stereochemistry of bonds and lone pairs. This three-dimensional model kit will also make models of $BeCl_2$, BF_3, CH_4, PCl_5, and SF_6; these models are useful when teaching hybridization and molecular shapes.

Making models using toothpicks and Styrofoam balls is another option if cost or the ability to obtain purchased model kits is an issue. Use Styrofoam balls of varying sizes and textures (e.g., smooth-textured ones for electron pairs and rough-textured ones for atoms); these are also useful for illustrating the shapes of molecules.

Ionic Formulas with Tab and Notch Cards

Students can discover how positive and negative ions form ionic compounds by pairing heavyweight paper cutout ion models made from patterns in the book *Chemistry Math Concepts (15),* which costs about \$20. These patterns can be enlarged and lengthened so that the Braille lettering can fit on them. The positive-ion Braille cards are notched for each lost electron, while negative ions are tabbed to represent each electron gained. The notches (the positive ions) combine with the tabs (the negative ions) so that the total of tabs and notches is equal, indicating a net charge of zero. Figure 4 shows examples of these cards. Binary and polyatomic compounds are made by labeling the cards; for example, a card with two negative notches is labeled as either the oxide anion or the sulfate anion. This activity provides students with practice in both formula writing and ionic compound naming.

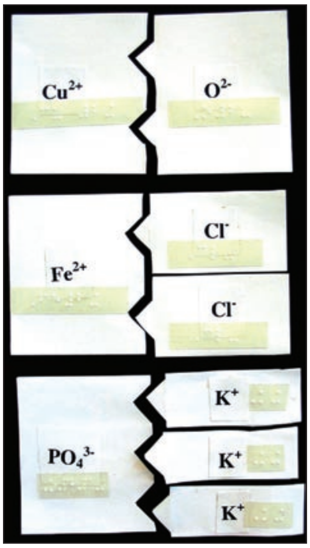

Figure 4. Notched Braille cards illustrating ionic bonding between cations and anions.

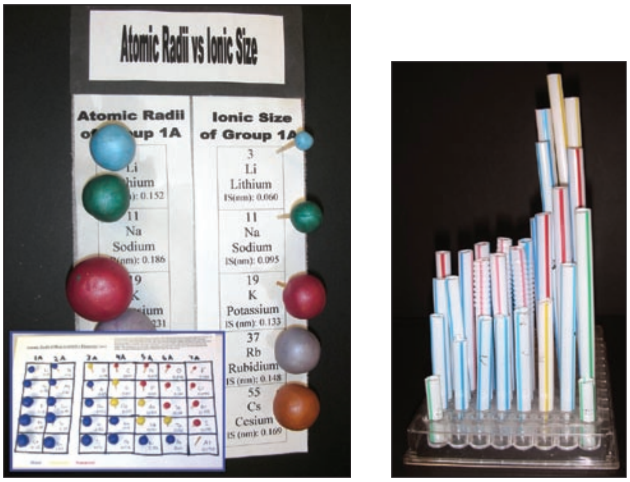

Figure 5. Tactile periodic trends' models made of clay (left) and plastic drinking straws (right).

Periodic Trends

Two examples of the periodic table model (Figure 5) convey trends in atomic or ionic radii in a tactile manner. A series of clay balls, representing s- and p-block atoms or ions (by way of differing size), and toothpicks, are placed in boxes in the periodic table. For atoms, the size of the ball increases from top to bottom in each column and decreases from left to right across each row. To help sighted students, the color of the clay can vary, showing where metals, non-metals, and metalloids are located in the periodic table (Figure 5, left).

Periodic trends can also be demonstrated by cutting drinking straws to a scaled length that represents atomic or ionic radius, electronegativity, ionization energy, or electron affinity. In the case of electron affinity, the absence of a straw indicates an element (such as Mg or a noble gas) for which the electron affinity is endothermic. The cut drinking straws are placed in position in a standard 96-well reaction plate (8 × 12 wells), the cost of which is less than $2. The 8 columns are convenient for representing the 8 groups of s- and p-block elements in the periodic table. The length of each straw is scaled to fit a dimension such as atomic radius, where 1 in. = 100 pm, and straws are cut with scissors after measuring with a Braille ruler. Once the rows of straws are cut and positioned in the wells, a three-dimensional plot of periodic trends is observable (Figure 5, right).

A Tactile, Two-Dimensional Model Kit for Organic Molecules and Reactions

Another low-tech tool that can assist blind students in organic chemistry is a two-dimensional organic chemistry molecular modeling kit *(16)*. The kit consists of different Velcro-backed paper symbols and a piece of felt-covered poster board, which may be folded in half for better portability. Cut-out poster board circles of equal size are made to represent carbon atoms. Velcro placed on the backs of these circles allows them to stick to the board. Smaller rectangles made with Velcro represent chemical bonds. Additional circles are labeled in print and Braille to represent other common atoms such as oxygen, nitrogen, sulfur, chlorine, bromine, and fluorine. Added shapes, such as hexagons or pentagons, are useful as wild-card atoms—the meaning, defined by the student on quizzes or exams, changes from mechanism to mechanism. The student can also utilize pie wedges with Velcro on one or both sides to represent stereochemistry. Pie wedges with Velcro on both sides represent atoms below the plane of the page, while pie wedges with Velcro on only one side represent atoms above the page. The total cost of the materials needed to make this tool is less than $5, and all materials are found in arts and crafts stores.

Conclusions

Over the past several decades, students who are blind or have low vision have increasingly moved from traditional residential schools to more typical classrooms, a trend that is popularly known as "mainstreaming". Low-cost audible and tactile tools can be of great value to teachers who are faced with the new experience of presenting chemistry to these students. These tools enable teachers to provide a more independent and rewarding laboratory and classroom experience for students with visual impairments and their sighted peers. In chemistry classes and laboratories, active participation and learning will lead to more positive attitudes about science among students who are blind or visually impaired. We anticipate other possible benefits as well, including higher expectations by teachers and sighted peer students, and greater retention of students who are blind or visually impaired in postsecondary study of science, technology, engineering, and mathematics.

Acknowledgments

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