The Quest for a Clean Drink

ABUL K.M. MUNIR

Water in India and Bangladesh is contaminated with arsenic, but chemistry has solutions.

By Christen Brownlee

In the United States and many other countries, getting clean drinking water is relatively easy. Just turn on the tap and out it comes. But not everyone has it so lucky. In some countries, getting a glass of clean water is a luxury—and in a few places, such as India and Bangladesh, it could mean the difference between life and death. In these countries, located next to each other in Asia, the drinking water on which millions of citizens rely is contaminated with arsenic.

Enterprising scientists have recently devised ways to remove arsenic from drinking water. Three of them—Abul Hussam, associate professor of chemistry and biochemistry at George Mason University, Fairfax, VA; Arup K. SenGupta, professor of chemical engineering and of civil and environmental engineering at Lehigh University, Bethlehem, PA; and Phil Souter, a chemist at Procter & Gamble—along with their colleagues have been so successful that they have received awards worth $1 million, $200,000, and $100,000, respectively, by the prestigious National Academy of Engineering, Washington, DC.

The techniques created by these scientists are water purification systems that are both easy to use and affordable by the people who need them the most—those who live in some of the poorest areas of India and Bangladesh. These systems have worked so well that they are now distributed to an increasing number of locations throughout India and Bangladesh.

Contaminated and deadly water

Decades ago, the people of India and Bangladesh relied mostly on surface water, such as ponds, lakes, and rivers. Water from these sources helped cook their food, clean their bodies, and quench their thirst. But growing populations and bad sanitation resulted in tainted surface water, making people sick when they drank it.

In the 1970s, some engineers and aid organizations came up with what seemed to be a perfect way to avoid microbes, but they did not consider monitoring water quality. By drilling shallow wells called tube wells between 30 and 150 feet into the ground, people could access groundwater that had been naturally filtered through the soil and that did not contain microbes.

Unfortunately, groundwater from many areas contained inorganic arsenic species, called arsenite (H_3AsO_3) and arsenates

ABUL K.M. MUNIR

SONO filter created by Abul Hussam.

($H_2AsO_4^-$ and $HAsO_4^{2-}$), which are deadly chemicals. About 20 years later, tests showed that thousands of tube wells were pumping out water brimming with arsenic.

The three arsenic species are a natural part of rocks and soil, but they don't pollute the surface water because they bind to iron hydroxide ($Fe(OH)_3$), a compound abundant in soil. But underground, different types of bacteria reduce the ferric ion (Fe^{3+})—one of the two ions making up $Fe(OH)_3$: Fe^{3+} and OH^-—to ferrous ion (Fe^{2+}), which is more soluble than ferric ions and breaks apart from the arsenic, releasing it into the subsurface water.

The effects of arsenic from drinking water on human health are not immediate, but over time, the poisonous water can cause cancer and death. Hard, dark patches on the skin appear first and are followed by nerve damage, often in the hands and legs, which can lead to their amputation, as well as liver cancer and kidney failure. Over a few years, a person drinking arsenic-contaminated water often dies from arsenicosis, a type of slow arsenic poisoning.

Using buckets to make filters

When Hussam discovered that his own relatives—who live in a district of more than half a million people in a part of Bangladesh called Kushtia—had been drinking arsenic-laced water, he decided to find a solution. In 1997, he started measuring the water's arsenic content and developing a filtration system that could remove the toxic arsenic species pumped from tube wells.

Hussam and colleagues made a prototype filter that uses two buckets piled on top of each other. Water is first poured into the topmost bucket, and then it passes through a special material called a composite iron matrix, which is a mixture of iron and iron hydroxide.

Manganese in the matrix catalyzes the transformation of the more toxic arsenite to arsenate ions. These ions bind to the surface of iron hydroxide particles as follows:

$$-\mathrm{Fe}-\mathrm{OH} + H_2AsO_4^- \rightarrow -\mathrm{Fe}-\mathrm{OAsO_3H}^- + H_2O$$

$$-\mathrm{Fe}-\mathrm{OH} + HAsO_4^{2-} \rightarrow -\mathrm{Fe}-\mathrm{AsO_4}^{2-} + H_2O$$

ARUP K. SENGUPTA

Hand pump water treatment unit developed by Arup K. SenGupta.

In these chemical reactions, the arsenate ions are shown binding to hydroxide groups (–OH) present on the surface of the iron hydroxide particles, while the iron atoms (Fe) are bound to atoms inside each iron hydroxide particle (hence the lines referring to such bonds deep within each particle).

When the water goes through the second bucket, layers of sand and charcoal remove the solid iron hydroxide particles with their load of attached arsenic, along with other chemicals that were not trapped in the top filter. After crossing this second bucket, the water is then collected in a container.

"We didn't test this prototype filter in the lab—we tested it with real groundwater, right in the fields of Bangladesh," Hussam says. "We thought that if it works with water that people take home to drink, then we can continue working on it. Otherwise, we would have to go back and try something else."

Luckily, Hussam's prototype worked very well and after it was optimized in 2000, he and his team started manufacturing the filters in bulk. Now, more than 72,000 of these bucket filters have been distributed under the brand name SONO in Bangladesh. Each costs about $40 and lasts at least five years.

By the most important measure—people's health—the filters are working. "People affected by arsenicosis who have been using the filters for the last two to four years have seen their disease reverse, and they feel better," Hussam says.

Removing arsenic directly at the pump

Filtering water after people carry it home is not the only fix for arsenic contamination. SenGupta came up with a solution that traps arsenic at villagers' water sources: the tube wells.

Each tube well supplies water for about 200 families. Every day, members of these families—usually wives or daughters—head to the central tube well to fetch water. They draw it using a hand pump and then carry it home in buckets. "We thought that it was much better, more efficient, and cheaper to remove arsenic directly at the pump," SenGupta says.

SenGupta and his graduate students worked with the Bengal Engineering and Science University, Shibpur, India, to make a treatment unit that would not use electricity (since electricity is not reliable in many villages) and would be easy to operate. Most villagers collect water by going to a tube well, cranking the hand pump, and catching the water, so the new treatment unit was designed to allow villagers to collect water in the same way.

GREG ALLGOOD, PROCTER & GAMBLE

Thousands of Indian children such as Love Singh (right) have benefited from an arsenic removing powder developed by Procter & Gamble.

The treatment unit is a stainless steel column containing a substance called an adsorbent—alumina (Al_2O_3) or a polymer—which attracts other molecules to its surface and is attached to the tube well's hand pump. As a villager cranks the hand pump, the device makes water (H_2O) coming up from the well sprinkle through the air, bringing it into contact with oxygen (O_2). This oxidizes iron present in groundwater to form iron hydroxide, which separates from the water:

$$4\,Fe^{2+} + O_2 + 10\,H_2O \rightarrow 4\,Fe(OH)_3 + 8\,H^+$$

Then both iron hydroxide and adsorbent catch arsenic from the contaminated groundwater, making it safe to drink. Over 8 to 10 months, the adsorbent in the filtering devices is depleted, and the villagers need to regenerate it. They can do so by going to a central regeneration facility where the adsorbent is reactivated. The villagers also strip the filters of the trapped arsenic and package it for safe disposal.

"How you handle arsenic disposal is as important as making the water fit for drinking," SenGupta says. "For that purpose, in every village, a committee consisting mostly of women is responsible for running the day-to-day upkeep of the arsenic removal units."

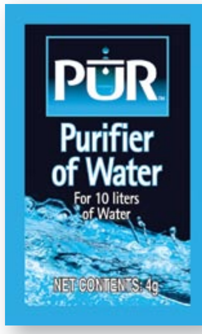
About 175 of SenGupta's hand pump filters are now already in use in India. "About 150,000 people are drinking safe water right now thanks to this hand pump filter," SenGupta says. "We want to keep that number growing!"

Arsenic-removing powder

In most industrialized countries, arsenic is usually removed from water through a water treatment plant. But building such facilities in some parts of India and Bangladesh, where hundreds of millions of people live in villages, is too expensive. Souter and his colleagues at Procter & Gamble came up with a different solution based on the same concept—small packets containing a powder that people can take with them.

"Most municipal water treatment facilities have a standard mix of chemicals that cities try to fine-tune based on local water quality," Souter says. "But people in developing countries—including India and Bangladesh—usually don't have the luxury of knowing what toxic stuff lurks in the water they need to drink. So we came up with a solution that would clean the water from arsenic, even if people don't know if there is arsenic in the water."

Souter and colleagues tested chemicals similar to the ones used in water treatment facilities but found a way to pack these chemicals into a pouch the size of a ketchup packet. Similar to what happens in large water treatment facilities, these small packets work in three steps called coagulation, flocculation, and disinfection.



PROCTER & GAMBLE

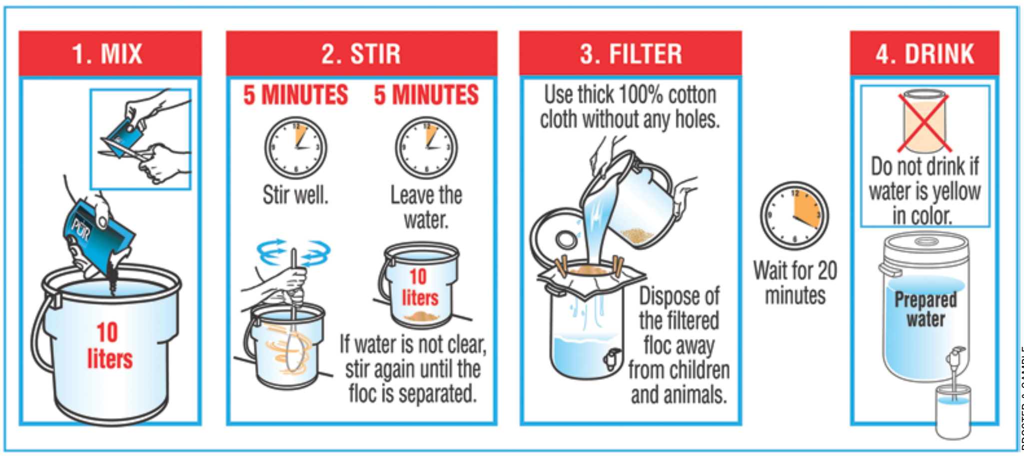
Front of the pouch containing arsenic-removing powder.

First, the contents of a packet are stirred into a bucket of water for five minutes while a chemical called ferric sulfate makes heavy metals—such as arsenic—and minerals precipitate or "coagulate" out of the water into tiny, sand-like grains.

Next, a polymer in the chemical mixture pulls the grains into big clumps, which settle at the bottom of the bucket in a process called flocculation. While the grains and clumps form, a chlorine-based disinfectant kills bacteria in the water.

The water is then poured through a clean cloth to filter out the clumps, and after 20 minutes—the time necessary for the water to be disinfected—the water is ready to drink. "Imagine the water starting out brown and foul, then finishing up clear and clean—that's how this product works," Souter says.

One packet cleans 10 liters of water—about the same amount a person can carry home from a tube well and enough drinking water for a family of four each day. Each packet costs about three cents, a price that is often paid by humanitarian groups.



PROCTER & GAMBLE

The PUR packets developed by Phil Souter and collegues work in four steps: mix, stir, filter, and drink.

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Although many people in India and Bangladesh cannot get tap water, these three techniques are still providing them with clean water and may prevent an increasing number of them falling victim to arsenic poisoning. Sometimes, small devices with the right type of chemistry can have a tremendous impact on people's quality of life!

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Teacher's Guide

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The Quest for a Clean Drink

Background Information

More on properties of water

When talking about water, we are almost always referring to a solution with water as the main ingredient or solvent. Except for very special laboratory situations, pure water does not exist. Even triple-distilled water very quickly dissolves atmospheric gases, particularly carbon dioxide. When talking about "clean" drinking water, it might be better to assume we are referring to "safe" drinking water. Depending on its source, drinking water has a whole host of dissolved substances (as opposed to suspended particles) as well as some living organisms, particularly bacteria and viruses. Water that looks clean because it is transparent and essentially colorless may not be safe. It is most certainly not pure.

Water as a chemical substance is unique in a number of ways. Even though its molecular mass is rather low (18 amu), it exists primarily as a liquid at room temperature rather than a gas (compare with ammonia, NH_3, molecular mass 17 amu). The angular molecular structure produces a polar molecule that is quite "sticky" in terms of intermolecular bonds (hydrogen bonds in this case). This is not the case for methane, as methane does not exhibit hydrogen bonding; hence the difference in terms of its primary physical state at room temperature—a gas rather than a liquid. [It might be useful here in class discussion to also mention to students the ammonia molecule and to make comparisons of this molecule's properties to those of water and methane, since ammonia is also a polar molecule.] The polarity of water also gives it the ability to dissolve so many other chemicals, hence the designation of "universal solvent". Is it any wonder that our bodies are 70 percent (by weight) water? And of course, water "hangs around" the earth because of its "stickiness" (intermolecular bonds) and resultant boiling point much higher than an environmental temperature of 25^{o}C.

Water has some other interesting properties that make for good living conditions on Earth. The fact that water expands below 4.0 ^{o} C. rather than continuing to contract as most substances do means that bodies of water have ice on the surface (a good insulator), rather than freezing from the bottom up. This same water has a high heat capacity per unit of weight—ten times that of more dense metals such as copper and iron, for instance. It is this high heat that helps to moderate the earth's temperatures where the oceans and other bodies of water act as heat sinks. This prevents large fluctuations in environmental temperatures. It has one of the highest heats of vaporization (2268 joules per gram at 100 ^{o} C).

Distribution of water in the world breaks down into some interesting and not obvious statistics. The world's oceans contain about 97.2% of the total water on earth. The balance of 2.8% is fresh water. That 2.8% breaks into the following:

- 2.11 % is trapped in glaciers and ice caps
- 0.62 % is groundwater
- 0.009 % is found in lakes
- 0.001 % is atmospheric moisture
- 0.0001% constitutes rivers

Any of the above can be a source of drinking water with a variety of extraction and treatment procedures. It is the source that determines what might be mixed with water to make a solution (assuming no suspended particles that may or not settled out). Looking at the world overall, there are 1.1 billion people (18% of the world's population of 6.2 billion) who lack access to safe drinking water. Related to this issue is the fact that about 2.6 billion people (42% of the total) lack access to basic sanitation which can also affect the quality of water supplies. See http://www.un.org/waterforlifedecade/factsheet.html, a source of basic statistics on the world-wide water situation. In parts of the United States, China, and India, groundwater is being consumed faster than it is being replenished.

- More than 2.2 million people (mostly from developing countries) die each year from diseases associated with poor water and sanitary conditions.
- Every week an estimated 42,000 people die from diseases related to low quality drinking water and lack of sanitation. Over 90 % of the deaths are children under the age of 5.
- Two of the water-related diseases, diarrhea and malaria, ranked 3rd and 4th place in the causes of death among children under 5 years old, accounting for 17 percent and 8 percent respectively of all deaths.
- In sub-Saharan Africa, a baby's chance of dying from diarrhea is almost 520 times the chance of that in Europe or the USA.
- Poor health resulting from inadequate water and sanitation robs the children of schooling and the adults of earning power, a situation aggravated for the women and girls by the time-consuming daily chore of collecting water.

More on solution chemistry

Considering drinking water as a homogeneous mixture or a solution, it is possible to analyze the contents of this water. The US government (Environmental Protection Agency, EPA) has established water quality standards for a large variety of dissolved substances (solutes), as well as bacteria, using *coliform* bacteria counts to indicate levels of bacterial contamination. http://www.epa.gov/OGWDW/. Protozoa such as *Cryptosporium parvum and Giardia lamblia,* which are parasitic pathogens, are also under quality control of the water industry and health officials.

Looking at drinking water from almost any source, several categories of solutes in the water sample will include inorganic and organic chemicals in elemental, molecular and ionic form. There is a plethora of tests for many of these particular chemicals to determine both their presence or absence, and their concentration. Your local water company is required to test for various dissolved substances, and for bacteria. These reports are often mailed annually to households and are available upon request. The following is a list of substances tested for in water samples:

- Turbidity
- Total Organic Carbon (% removal)
- Disinfectants and Disinfection By-Products
  - Chlorine residual
  - TTHM (total trihalomethanes from chlorine interaction with organics)
  - HAA-5 (haloacetic acids five)
- Copper
- Arsenic
- Lead
- Nitrate (as nitrogen)
- Barium
- Chromium
- Nickel
- Volatile Organic Contaminants, Synthetic Contaminants
- Radioactive Contaminants (gross Alpha, combined radium, uranium)
- Total Coliform bacteria, Fecal Coliform and E. coli bacteria

HAA-5 (3, above) refers to a group of chemicals that are formed along with other disinfection byproducts when chlorine or other disinfectants used to control microbial contaminants in drinking water react with naturally occurring organic and inorganic matter in water. The regulated haloacetic acids (HHA-5) include monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid and dibromoacetic acid. These acids can be further transformed into the trihalomethanes that are considered carcinogenic. The most recent EPA regulations limit HHA-5s to 60 ppb (annual average).

(See http://www.epa.gov/enviro/html/icr/gloss_dbp.html.)

More on water purification

Water that is to become municipal drinking water is treated in a variety of ways to ensure that is safe to drink. Depending on the source (a river vs. aquifer or artesian well water), it may be first screened, then treated with chlorine (which can kill or inactivate bacteria and viruses but not protozoan pathogens, such as *Giardia* and *Cryptosporium*) before being treated in a flocculation tank using the chemicals aluminum sulfate (alum), $Al_2(SO_4)_3$, and calcium hydroxide (slaked lime), $Ca(OH)_2$. These chemicals react to form aluminum hydroxide, $Al(OH)_3$, a sticky material that traps suspended particles which then precipitate. This is known as flocculation. The liquid is then passed through a sand filter to remove any unprecipitated flocculent. Sand filtration or other types of filters will also remove the pathogenic protozoa that are not killed by chlorination. Additional chlorination follows along with aeration (for taste enhancement), pH adjustment and fluoridation (1 ppm). The adjustment in pH is necessary because, if the water is acidic, it will react later with domestic water pipes, releasing, among others, undesirable Cu^{+2} and Cd^{+2} ions into a household's water pipeline. The water is now ready for public consumption.

Chlorination or chlorine addition to domestic water supplies takes place in one of three ways:

- Chlorine gas is bubbled into the water,
- A water solution of sodium hypochlorite, NaOCl is added,
- The solid, calcium hypochlorite, $Ca(OCl)_2$, is added to the water.

The chemistry of this particular treatment is the production of a weak acid, hypochlorous acid, HOCl. How this compound inactivates or kills bacteria and viruses is not clearly understood but is thought to damage the selective permeability of the cellular wall which in turn is not able to control the entrance/exit of various chemicals that diffuse in and out of the organism's cellular interior (cytoplasm). Some waterborne viruses, such as enteric viruses and hepatitis A may be more tolerant to chlorine disinfection than some bacterial species, but it is not well understood how chlorine inactivates viruses. See http://www.sciam.com/article.cfm?id=how-does-chlorine-added-t.

An interesting aside is the fact that bacteria along with some other organisms both microscopic and macroscopic (water hyacinths) are being studied for use in "cleaning" contaminated water of trace amounts of certain metals including zinc, selenium and even arsenic. Researchers are working with sulfate-reducing bacteria (SRB) that normally bind sulfate in oxygen-free water. Found in a flooded lead and zinc mining tunnel in Wisconsin, the species from the *Desulfobacteriaeceae* family of bacteria can survive in low oxygen environments and bind zinc with sulfate, forming spheres with zinc concentrations a million times higher than that found in the surrounding water. These bacteria have the potential to remove zinc, selenium, and even arsenic traces from various water sources.
http://www.sciam.com/article.cfm?articleID=000E6700-23DF-1C68-B882809EC588ED9F

Additional living "filtering" systems include the water hyacinth, which has been known to extract many heavy metals from water systems, concentrating them in the root system. Experiments with the roots dried into a powder have shown that the powder added to arsenic-contaminated water reduces the arsenic levels to the World Health Organization's safe limit of 10 micrograms per liter, even if initial concentrations are 20 times as high. Check out
http://www.newscientist.com/channel/health/mg18524916.200-rooting-out-arsenic-in-bangladeshi-wells.html.

While using the water hyacinth as a filtering system may seem very attractive, water hyacinths are banned in many states because once released into water systems, they can take over an ecosystem, causing the usual crowding out of other aquatic plant species, subsequent interference with the food chain that supports a variety of animal life, and the proverbial eutrophication of a water system from the death and decay of the hyacinths, creating reduction of dissolved oxygen which affects many larger aquatic species, particularly fish. Even so, the plants are part of some water treatment facilities for heavy metal removal.

Another recent water purification design makes use of nanoparticles of magnetite (magnetic iron oxide). Arsenic binds strongly to iron oxides. The magnetite nanoparticles are 12 nanometers wide—smaller than a virus. Using such small particles means a very large surface area, high contact, and short diffusion times (the time for the particles to grab a particular chemical of interest). The magnetite particles react with the arsenic. In the presence of a weak magnetic field, the nanoparticles begin to clump and separation can be accomplished. This kind of separation using magnetism is more efficient and less expensive than normal filtration. Further reductions in cost will be accomplished by substituting iron oxide nanoparticles from olive oil and rust for the expensive magnetite. http://www.sciam.com/article.cfm?id=rust-could-be-the-key-to

An interesting new "smart" material is being evaluated that both detects and helps to eliminate organic water pollutants (chlorinated phenols found in preservatives, insecticides, and produced by paper mills, plastic and paint manufacturers). It is zinc oxide (ZnO). The important property of zinc oxide is its ability to emit visible light when it is exposed to ultraviolet light. When zinc oxide is exposed to the chlorinated phenols in water, its light emission decreases. This response is measurable for pollution concentrations as low as 1 ppm and takes less than a minute to occur. In addition, with the detection of the organic molecules, the ZnO can act as a catalyst in the breakdown of the molecules utilizing UV light. With conversion of the organics to harmless molecules, the ZnO again glows more brightly—indicating that the job is done. This material is considered to be a nanosensor.

Another design proposal for filtration utilizes recycled rubber tires which are ground up into crumbs (1-2 mm across). The system (now patented) is touted as being four times faster than standard filtration systems using sand, charcoal and stones of various diameters. The tire system uses tire crumbs of different sizes, starting with the largest crumbs at the top, with a gradient of smaller sizes progressing to the bottom (exit). If the system is used to filter wastewater, larger particles are trapped at the top and do not clog the system further down. A concern for this system using tires is the possibility that old tires may leach toxic chemicals, including heavy metals. Testing of the system and scaling up to full size is ongoing. See http://www.newscientist.com/article.ns?id=dn10637&print=true.

The history of water filtering can be found at http://www.historyofwaterfilters.com/.

Connections to Chemistry Concepts

1. **Polymers**—Larger molecules that can be used to attract coagulated ferric sulfate-based heavy metals, including arsenic, producing an even larger "clump" or flocculant for easier removal from treated water
2. **Organic compound**—Being carbon-based, these can form large molecules that are useful in filtration systems and the coagulation-

flocculation of compounds that need to be removed from water systems.

3. **Precipitate, water solubility**—Formed from a low solubility reaction product, the precipitation reaction is a useful way to selectively remove certain chemicals from solution. It is the basis for one water treatment process called flocculation.
4. **Ions**—These charged particles are able to be selected out of solution either in ion-exchange systems or as part of a chemical reaction in which undesirable heavy metal ions can be precipitated from solution.
5. **Oxidation**—This type of reaction is important in converting arsenic (by increase in oxidation number) as the arsenite ion (+3) to less toxic forms, such as the arsenate ion (+5), which can be bound to iron(III) hydroxide for removal in some of the low-cost tech devices created for water purification in poor countries.
6. **pH**—The conversion of various arsenic compounds to other forms is pH-dependent. Certain enzymes (catalysts) and important soil bacteria will only function in a particular pH range.
7. **Adsorb(ent)**—This process is defined by the fact that molecules are attracted and held on the surface of some material. This is in contrast with absorption in which chemicals not only are attracted to the surface of a material but also penetrate to the interior of the material (diffuse). This process is the basis for iron hydroxides attracting arsenic compounds, but it is dependent on the pH of the reacting solution medium as well as the oxidation state of the arsenic.
8. **Secondary bonding**—Hydrogen bonding between water molecules gives rise to an entirely different set of properties from those of methane, which relies solely on van der Waals forces and does not exhibit hydrogen bonding.

Possible Student Misconceptions

1. **"Adding soap to water when making bubbles works because the soap makes the water molecules stick together."** *Actually, the soap works to break the water molecules apart! The strong hydrogen bonds of water make it difficult to "stretch" the water into bubbles. The surface tension of pure water is broken through the addition of soap and the water is "stretched" with the soap molecules connecting to each other and to the water molecules.*

2. **"Water softeners use salt as part of the water treatment. Therefore, the softened water is salty."** *Actually, salt is used to flush the hard water ions (primarily Ca^{2+}, Mg^{2+} and Fe^{3+} ions) out of the exchange resin in the water-softening device at the end of the cycle. During normal use the resin exchanges sodium ions for the hard water ions of calcium, magnesium and iron. Eventually, the resin is filled with these hard water ions and must be replaced with new sodium ions. This is done with a wash of salt water which replaces the hard water ions once again with Na^+ ions and the*

system is ready to begin again. The hard water ions do not get into the house's water supply because the ions are flushed down the drain, usually at night.

3. **"Water for drinking is pure water."** *As noted in the article, Asian countries in particular have problems with arsenic contained in their drinking water. And although it is relatively easy to obtain clean drinking water in the U.S., even here drinking water is not pure. It is clean enough to drink, but it contains all kinds of dissolved chemicals as well as bacteria and viruses (dead and living). As noted in the opening paragraph of "More on properties of water", truly pure water is very difficult to obtain.*

4. **"If one melts snow, one gets pure water."** *As this Teachers Guide was being researched, scientists at Louisiana State University published in the journal, Science, their findings that snowflakes contain bacteria. It has long been known that water, either as raindrops or as snowflakes, requires nucleation sites, tiny objects on which to collect while in the atmosphere. It had been believed that the two main global nucleators were dust specks blown up into the atmosphere over deserts and dry areas, and tiny salt crystals thrown up over the oceans by wind and wave action. The LSU researchers and colleagues at the National Agronomy Research Institute in Montfavet, France, and at Montana State University in Bozeman, Montana, have discovered that most frequently (as much as 85% of the time) those nucleation sites are airborne bacteria, most commonly Pseudomonas syringae, a bacteria that can affect plants. For more information, you can access a review of the article at the CNN news online website at* http://edition.cnn.com/2008/TECH/science/02/28/snow.bugs.ap/index.html. *This is the reference for the actual article:* Science *29 February 2008:*
   Vol. 319. no. 5867, p. 1214. You can view the abstract at http://www.sciencemag.org/cgi/content/abstract/319/5867/1214 *and, if you are* a subscriber to *Science, you can view the entire article online at this same URL.*

Demonstrations and Lessons

1. There are many programs already available that use water as a major topic within the chemistry curriculum. The most obvious one is the ACS Chemistry in the Community (ChemCom) program. (see the first title listed in the reference section for ordering). A variety of chemistry topics can be taught through the first unit in the text (activities are integrated into the text). One impressive activity for students is to "purify" a water sample (called "Foul Water") that is

odorous, oily, “gunky”, and seemingly impossible to clean up. Going through the various steps using very common equipment, students end up with what appears to be a colorless, clear, and odorless liquid. They have performed a microscale water purification process as done in municipal water treatment facilities. Other activities include:

- Water testing for common ions such as iron, calcium, sulfate, and chloride
- Determining the solubility of a chemical substance
- Solubility limits of ions and polar/non-polar substances with a particular solvent
- Water softening

2. A plethora of activities related to water studies can be found at the Rivers Project, http://www.siue.edu/OSME/river/index.html and http://www.siue.edu/OSME/river/Ordering%20Materials/Order.html
3. For some visual programs to help illustrate polarity and hydrogen bonding of water molecules refer to http://programs.northlandcollege.edu/biology/Biology1111/animations/hydrogenbonds.html.
4. A demonstration to illustrate the effect of hydrogen bonding on the viscosity of a liquid can be shown by slowly pouring three different 3-carbon alcohols with different numbers of hydroxyl (-OH) groups attached. The one-OH alcohol is propanol, the two-OH alcohol is 1,2-propanediol (propylene glycol), and the three-OH alcohol is 1,2,3-propanetriol (glycerol or glycerin).
5. A complete description of an experiment to measure surface tension of water (pure and with additives) can be found at https://www.sciencebuddies.org/mentoring/project_ideas/Phys_p012.shtml?from=Home. This material includes lesson plans, complete instructions for building the important balance beam needed for measurement as well as references. For other activities related to surface tension from the same program, Science Buddies, click on http://www.sciencebuddies.org/science-fair-projects/search.shtml?cx=006938645102073751460%3A5g77bgclmby&q=surface+tension&sa=Search&cof=FORID%3A9#894. The home page for Science Buddies is http://www.sciencebuddies.org/.
6. Water filters that are used in the home (and industry for that matter) utilize exchange resins. Something like a Brita filter can be opened to show the resin. If can also be used to test its effectiveness with tap water. A lab activity can be organized in which students first test local tap water and distilled water for some of the ions known to be removed by the Brita filter—iron, chlorine as chloride ion, copper, and zinc. The resin also affects pH of the water sample which should be tested. The Brita filter reduces lead and copper [93%], zinc and particulate matter (non-chemical), along with Mg and Ca, so that water should be soft. The charcoal removes taste, odor and chlorine. And there is a small amount of silver for bacteriostatic action. Testing for the presence of these ions can be done with test kits available from the major science supply companies. Or check the listings in the Rivers Project above (#2) for chemical test equipment.

Students could also test for some other common ions such as carbonate ion (CO_3^{-2}), sulfate ion (SO_4^{-2}), and the magnesium ion, (Mg^{+2}). A standard pH test should also be performed. As part of the test, water samples should also be boiled to see if the pH changes (increases) due to the elimination of dissolved carbon dioxide gas—a good way to help students understand that distilled water in the laboratory is acidic, not neutral. Some useful references to illustrate how an ion exchange works can be found at http://wiki.biomine.skelleftea.se/wiki/index.php/Ion_exchange, http://www.ionexchange.books.kth.se/applets.html and http://www.dartmouth.edu/~chemlab/chem3-5/ionx1/overview/procedure.html.

7. A more extensive water studies program that involves field work (the source of the water!) and related activities other than those listed in the Rivers Project above (#2) can be found at the Access Excellence website, http://www.accessexcellence.org/AE/ATG/data/released/0249-JudyWilliams/description.html.
8. An interactive for students that lets them clean up an oil spill is found at http://www.units.muohio.edu/dragonfly/water/h2oindex.shtml. Other activities at this website include “Learn how you can help prevent pollution” and “Learn how environmental workers clean up oil spills”. There is background information on various aspects of water pollution.
9. The process of flocculation used in water treatment to settle out suspended material is accomplished using a combination of aluminum sulfate (alum) and calcium hydroxide (slaked lime). The reaction is as follows:

   $$Al_2(SO_4)_3\ (aq) + 3\ Ca(OH)_2\ (aq) = 2\ Al\ (OH)_3\ (s) + 3\ CaSO_4\ (aq)$$

   You could show this reaction in clear water with the formation of the white gelatinous precipitate of aluminum hydroxide.
   You could also prepare some “dirty” water by adding some clay soil to water, stirring, and pouring off the water suspension into a second container—leaving the excess undissolved soil in the first container. Then add the aluminum sulfate and calcium hydroxide to the suspension in the second container to see how much clearing of the water is accomplished by the reaction and formation of the gelatinous precipitate of aluminum hydroxide.
   You could also try to see the effect of various sized soil particles in suspension on the precipitate reaction’s ability to flocculate the suspended matter.
   For every 100 ml sample of water or solution, add a maximum of 3 grams aluminum sulfate to 2 grams of calcium hydroxide. Stir to dissolve the chemicals. (Some of the calcium hydroxide may be insoluble.)

Student Projects

1. Students could obtain information on water quality from their local water supplier. Water companies issue results of periodic tests on water samples. The EPA maximum levels for any one chemical are found either in the report or can be obtained from the EPA main website, http://www.epa.gov/OGWDW/ . Students could also check on the health effects from exceeding the maximum levels allowed for safe drinking water.

2. Students could set up a distillation apparatus for purifying a tap water sample, testing for the various dissolved substances in the sample before and after distillation (the collected distillate). A related research project would be to find where in the world desalination is used to produce drinking water. What is the energy source for running this kind of large-scale distillation? Is solar power possible for the energy source? Is distillation cost-effective for producing safe drinking water in poor countries? What kinds of water treatment are cost-effective in poor countries? A good starting point for this project might be http://www.coastal.ca.gov/desalrpt/dchap1.html or http://en.wikipedia.org/wiki/Desalination.

3. Students could test for the various common ions in and pH of bottled water. What is the source of the water—underground aquifers, stream or lake water, municipal water, USA or foreign? They could compare the components of their bottled water with what is found in their local tap water. Refer to the *Reader's Digest* article on bottled water, found at http://www.rd.com/special-reports/the-environment/rethink-what-you-drink/article.html.

4. Students could research the issue of mercury in water—what is the chemical form of the mercury, what is its source(s), how can mercury in the environment be reduced, what are the health effects of mercury on different age groups? See http://www.epa.gov/safewater/dwh/c-ioc/mercury.html.

5. If the testing of the resin from a Brita filter is not done as a whole class project, it can be done as a student project (see Classroom Activities, #5 above). Its effect on water softening can also be tested by using the standard "sudsing" test. In this test, a 5 ml sample of water is added to a test tube and one drop of Ivory liquid soap (NOT generic liquid detergent) is added. Stir the mix gently. Look for turbidity (cloudiness). Compare this sample with other samples (tap water without water softening treatment, distilled water). The greater the turbidity, the greater the quantity of soap dispersed (the softer the water). Stopper the test tubes with the soap added and shake vigorously. Check the height of the soap bubbles (suds)—the higher or the more suds, the softer the water. Another test for the hardness of water (the amount of magnesium and calcium ions in water) is to add 10 drops of a sodium carbonate solution to new 5 ml samples of water. Any cloudiness or precipitate is due to the presence of the magnesium or calcium ions that form the insoluble carbonate. How do the results of the "sudsing" tests and the carbonate precipitate tests compare? (See reference #1 for lab techniques and procedures.)

6. Students can do a study (long term) of a local stream or lake, using standard testing procedures including dissolved oxygen (electronic probes or chemicals) biological and chemical oxygen demand. There are standard textbooks on water ecology that include the various tests. Also, refer to the material available from the Rivers Project (http://www.siue.edu/OSME/river/index.html)

7. There is a whole world of interesting chemistry about arsenic that could be explored by students. It has a long history (starting with the Greeks and Persians) in its use for various medical treatments, beauty treatments and, of course, murder! A starting point is found at http://en.wikipedia.org/wiki/Arsenic.

8. Students can build a conductivity meter for testing relative concentrations of ions in various samples of water, including distilled and deionized water.

9. Students could research and report on the special properties of water and the effects on climate and life on Earth as a result of these special properties.

Student Questions

1. Why did the people of India and Bangladesh change from surface water to water from tube wells?
1. What is the source of arsenic found in water from tube wells?
2. How do certain types of soil bacteria (anaerobic) increase the amount of arsenic in water from tube wells?
3. What are some of the detrimental health effects from ingesting too much arsenic in water?
4. What is the chemical function of manganese that is used in the Hussam arsenic filter bucket?
5. What is the chemical function of iron(III) hydroxide in the Hussam filter bucket?
6. How does the SenGupta water filter work?
7. What are the three chemical steps used in the Procter & Gamble (Souter) device to clean water?

Answers to Student Questions

1. **Why did the people of India and Bangladesh change from surface water to water from tube wells?**
   People were looking for a water source that was free of bacteria. Normally water that passes through soil and rock is filtered, removing bacteria.

2. **What is the source of arsenic found in water from tube wells?**
   The arsenic is coming from rock and soil.

3. **How do certain types of soil bacteria (anaerobic) increase the amount of arsenic in water from tube wells?**
   Soil bacteria chemically destroy iron hydroxide that normally is able to bind up arsenate and arsenite ions

4. **What are some of the detrimental health effects from ingesting too much arsenic in water?**
Long-term effects from drinking arsenic-laden water include skin disorders, nerve damage, kidney failure, and liver cancer. Many of these effects are listed under the general term, arsenicosis, or arsenic poisoning.

5. **What is the chemical function of manganese that is used in the Hussam arsenic filter bucket?**
The manganese acts as a catalyst in the oxidation of arsenite ions.

6. **What is the chemical function of iron (III) hydroxide in the Hussam filter bucket?**
The iron (III) hydroxide binds the arsenate ions to its surface, causing them to no longer be dissolved in the water, according to these equations:

$$-\mathrm{Fe\,(OH)} + \mathrm{H_2AsO_4^-} \rightarrow -\mathrm{Fe{-}OAsO_3H^-} + \mathrm{H_2O}$$

$$-\mathrm{Fe\,(OH)} + \mathrm{HAsO_4^{2-}} \rightarrow -\mathrm{Fe{-}AsO_4^{2-}} + \mathrm{H_2O}$$

7. **How does the SenGupta water filter work?**
The SenGupta filter is placed inside a tube well hand pump. As the water rises into the hand pump, the water is exposed to air. This causes iron in the water to be oxidized to iron (III) hydroxide. This and the aluminum oxide in the pump tube both adhere to the arsenic compounds and remove them from the water.

8. **What are the three chemical steps used in the Procter & Gamble (Souter) device to clean water?**

From the addition of a bag of chemicals (ferric sulfate, a polymer, and chlorine compound), arsenic and various minerals first precipitate ("coagulate"), then clump together ("flocculate"). "Disinfection", the third step, is done with chlorine-containing compounds to kill bacteria.

Anticipating Student Questions

1. **"If arsenic occurs in soil and rock, what is the form of the chemical—element or compound?"** *Arsenic in rock or soil is usually found in compound form. Usually it is found in compounds as arsenite (oxidation state +3) and arsenate (oxidation state +5).*
2. **"How does arsenic act as a poison?"** *Basically, when arsenic is taken in by the cells of a living organism, the arsenic interrupts the*

energy-producing chemical cycle involving ATP. Arsenic in the form of arsenate readily passes through the cell membrane because it has similar chemical characteristics to phosphate, a family member. Various enzymes are inactivated, as occurs with other poisons such as cyanide. A living organism quickly runs out of vital energy production. This explains why arsenic compounds can be used to kill bacteria and fungi (wood preservative) and insects. Arsenic, as the compound arsenic trioxide, has also been used to treat cancer (leukemia). Before antibiotics, the arsenic compound arspenamine was used to treat syphilis and trypanosomiasis (sleeping sickness).

3. **"What are heavy metals and why are they a problem if found in drinking water?"** *Heavy metals are metallic elements with large atomic masses and generally high densities. They include such elements as mercury (Hg), lead (Pb), cadmium (Cd), and antimony (Sb). They are considered to be toxic because they interfere with the enzyme systems of living organisms. Normally, enzymes contain magnesium ions (Mg^{2+}), calcium ions (Ca^{2+}), or zinc ions (Zn^{2+}), in their structure. Heavy metal ions can displace the magnesium and calcium ions causing the enzyme structure to become inoperable.*
4. **"If water is recycled, how is it possible for me to be drinking water that previously was part of some animal in East Africa? My local water treatment plant is not connected to East Africa!"** *Water moves around the world through the water cycle. Water evaporated from a source in one part of the world can become part of a cloud system that can move to another location in the atmosphere—multiple changes from cloud to rain (precipitation) back to cloud can eventually move that East African water to the USA with one more transformation from cloud to rain to flowing water to a water reservoir above or below ground and transfer to a water treatment plant, then to a home's water faucet. One person's excretion is another person's drink of water, eventually!*

References

Chemistry in the Community, (ChemCom), 4th Edition, W.H. Freeman & Co., NY, ISBN 0-7167-3890-2, Unit 1, "Water: Exploring Solutions".

Chemistry in Context, Wm. C. Brown Publishers, Dubuque IA, ISBN 0-697-21948-8, Chapter 5, *"The Wonder of Water",* Chapter 7, "*Onondaga Lake: A Case Study"*.

Journal of Chemical Education, Vol.85, No.2 Feb. 2008, pp. 185-187, *"Water Streaming Chemistry",* Janice Hall Tomasik (www.JCE.DivCHED.org). This is a helpful article for teachers. The reference highlights the wealth of chemistry on the Internet, emphasizing sites that can be used as teaching tools, from building a solar-powered water desalination device to real-time geographic site data on daily stream flow conditions, state by state.

An interesting story about the possible arsenic poisoning of Napoleon when he was imprisoned on Elba Island is found in an earlier *ChemMatters* issue (December, 1998, p. 4, *"The Case of Napoleon Bonaparte").* This story is a good reading exercise for students because, if they do not read carefully, they will conclude that Napoleon died from an arsenic poisoning conspiracy rather than from his terminal cancer, which is well documented. On the other hand, it is possible that the arsenic found in his tissues may well have contributed to some debilitation and synergistic weakening with his cancer. The possibility of arsenic poisoning from the wallpaper with its Scheele's Green pigment (copper arsenic compound) is highly likely. But it did not kill him directly. So, this article can be used in the classroom for several purposes besides that of a mystery. There is some interesting history and chemistry here.

Another interesting read for students concerns the mysterious death of a deer! The chemistry behind the investigation and the data needed to reach some conclusion about the possible role of arsenic (and its sources) are part of the article, *"Mystery Matters—Deer Kill",* found in *ChemMatters*, October, 1992, pp. 12-14. Again, this article can be used with students for both critical reading and informative practical chemistry.

ChemMatters presents a modern murder mystery involving arsenic with additional historical information on arsenic in society in the article, "Poisoned!", in its December, 2005 issue on pages17-19. Unfortunately, this article is not available in the online content for the Dec. 2005 issue at this time, but you can access the Teachers Guide for the "Poisoned!" article (pp.52-61), which lists a whole host of additional references, classroom ideas, and related chemistry. The Teachers Guide is at http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_ARTICLEMAIN&node_id=1090&content_id=CTP_005702&use_sec=true&sec_url_var=region1.

Web sites for Additional Information

http://www.epa.gov/OGWDW/ is the basic website of the Environmental Protection Agency, with a variety of topics including drinking water quality, source water protection, drinking water standards, public drinking water systems, and an "A-Z" list of topics, among other things.

http://www.epa.gov/OGWDW/arsenic/index.html specific information on arsenic and its health effect, sources of contamination, EPA limits in water.

http://www.unsgab.org/docs/mdgs.htm United Nations Web site (for its Millennium Development Goals, MDGs) that deals with the world picture concerning the problems and some solutions for making safe water available to more people. It includes useful statistics.

A number of websites that provide lessons in water studies include: http://learnweb.harvard.edu/ent/gallery/pop4/pop4_7.cfm, http://www.siue.edu/OSME/river/index.html, http://www.siue.edu/OSME/river/Ordering%20Materials/order_chemistry.html, http://www.wateraid.org/uk/learn_zone/educational_resources/782.asp, http://ga.water.usgs.gov/edu/characteristics.html (source of pictures and explanations of various instruments and techniques used in water studies), http://ga.water.usgs.gov/edu/, http://www.vims.edu/bridge/ (primarily salt water teaching resources), and http://www.epa.gov/safewater/kids/wsb/ (water sourcebooks K-12 in pdf)

Water other than for drinking is needed in agriculture. A world view shows the common use of sewage water for crops and the potential health problems. See http://www.newscientist.com/article.ns?id=dn6297

An interesting problem in terms of availability of safe drinking water is that of providing water for astronauts. This article discusses why it might be necessary to use urine! http://www.sciam.com/article.cfm?id=new-menu-item-on-space-st

Several primers on the basics of water pollution, with diagrams, include http://www.umich.edu/~gs265/society/waterpollution.htm http://ga.water.usgs.gov/edu/specials.html, http://www.nlm.nih.gov/medlineplus/waterpollution.html, http://health.usgs.gov/dw_contaminants/, http://health.usgs.gov/dw_contaminants/arsenic.html, http://phys4.harvard.edu/%7Ewilson/arsenic/countries/arsenic_project_countries. html#USA (deals with distribution of arsenic in US waters as well as the other countries, including Bangladesh. It is part of a project at Harvard that provides a plethora of references, including criticism of various agencies attempts to deal or not properly deal with the water problems. http://phys4.harvard.edu/%7Ewilson/arsenic/arsenic_project_links.html is a related set of extensive references connected to the Harvard arsenic project.

An extensive set of references from the US Geological Survey in the basics of water sources including the water cycle, ground water, and locations worldwide of water can be found at http://education.usgs.gov/common/secondary.htm#groundwater

You can find an extensive collection of articles from the BBC news services on arsenic, including the most recent status of arsenic in Southeast Asian water. at http://search.bbc.co.uk/cgi-bin/search/results.pl?scope=all&edition=i&q=Arsenic+in+water&go.x=0&go.y=0&go=go.

An overview of the world problem of providing enough safe drinking water and impediments to the solution is found at http://www.sciam.com/article.cfm?id=the-challenge-of-sustaina.

A separate topic familiar to most students is bottled water. There are the issues of the water source, its safety, type of government regulation, and comparison of this water with regular tap water. Read all about it at http://www.rd.com/special-reports/the-environment/rethink-what-you-drink/article.html.