UNIT 10: ACIDS, BASES AND SALTS

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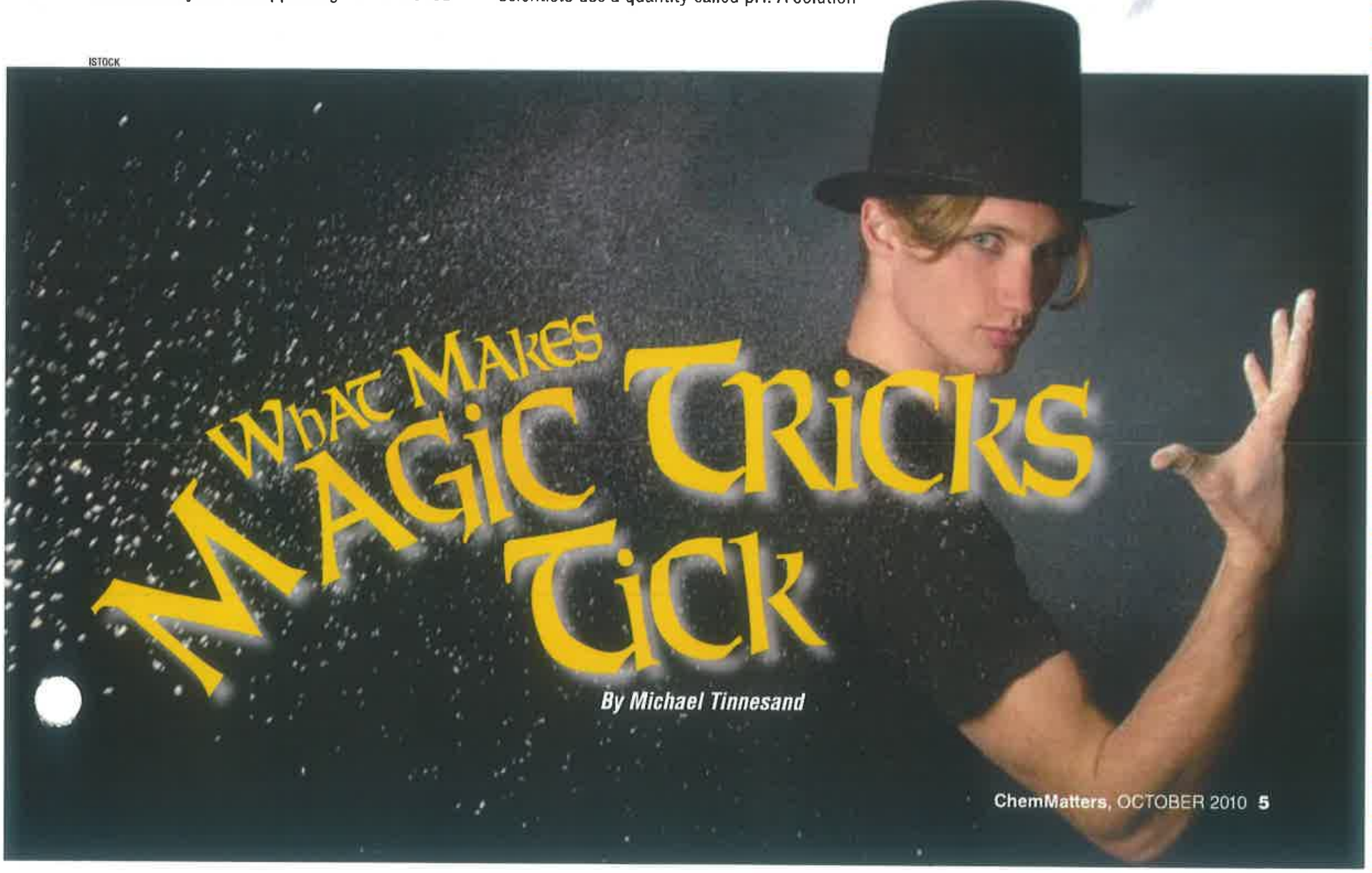


What Makes Magic Tricks Tick

By Michael Tinnesand

Two friends, Gary and Jim, walk through the crowded halls of a local high school. Without warning, a boy walking in the opposite direction reaches out and squirts something at one of the students. They look down to find a large splatter of blue ink across the front of Gary's shirt. The boy is lost in the crowd by the time they understand what has happened. As Gary waits in the principal's office to report the damage, he notices that the ink stain is beginning to fade. By the time the principal is ready to see Gary, the ink stain is totally gone! He has been tricked with "disappearing" ink.

Is this magic?

Good tricks usually have some features in common. The first is an element of surprise, a sense of sudden wonder or amazement, especially when due to something unexpected. We are all familiar with ink stains, and we know they are very difficult to remove from a shirt once they get on it. But in the case of the "disappearing" ink, the stain goes away all by itself, and it does so relatively quickly. Another feature of a trick is the absence of any apparent explanation for what happened. It is not clear why the "disappearing" ink vanished all by itself. But if someone repeated the trick and told you that it wasn't real ink—just a substance that looks like ink—you would probably be much less surprised or confused when the stain vanished.

We can be sure that these tricks are not due to "magic." Magic is a supposed supernatural force that allows impossible things to happen or that changes the laws of nature. The only reason something *appears* to be magic is when the cause of the change is a mystery to us. One of the roles of chemistry is to demystify the unknown or to explain what is not readily explainable.

Demystifying disappearing ink

How can we explain an unexpected change if it is not really magic? We can apply some chemistry. In the case of disappearing ink, the explanation is simple. The substance is not ink at all but a solution of a special chemical that can change color depending on how much acid or base is in the solution. This special substance is called an acid-base indicator. It turns into a different color when it goes from an acidic to a basic solution.

To tell whether a solution is acidic or basic, scientists use a quantity called pH. A solution is acidic if its pH is between 0 and 7 and basic if its pH is between 7 and 14. A very low pH means that a solution is vey acidic, and a pH close to 14 means that a solution is very basic (or barely acidic).

For instance, when an acid-base indicator called thymolphthalein is added to a solution, it is colorless when the pH of the solution is between 0 and 9.3 and dark blue when the pH is above 9.3 (Fig. 1).

When the disappearing ink is prepared, a strong base such as sodium hydroxide ($NaOH$) is added to the solution. This keeps the pH above 9.3, and the ink is blue. Things change when the ink is sprayed on clothing. Carbon dioxide (CO_2), which is always present in the air, reacts with the water in the solution to form carbonic acid (H_2CO_3). First, the carbon dioxide dissolves in the water and then very slowly reacts to form carbonic acid:

$$CO_2\,(gas) + H_2O\,(liquid) \rightarrow H_2CO_3\,(aqueous)$$

The carbonic acid rapidly neutralizes some of the sodium hydroxide in the solution, according to the following reaction:

$$2\,NaOH + H_2CO_3 \rightarrow Na_2CO_3 + 2\,H_2O$$

As the sodium hydroxide, which is responsible for the blue color and the high pH value, slowly vanishes from the solution, the pH decreases to the point that the thymolphthalein turns colorless. Not magic, just basic chemistry.

pH	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.	11.	12.	13.	14.
Thymolphthalein															

Figure 1. Thymolphthalein appears colorless in a solution with a pH between 0 and 7 and blue in a solution with a pH between 11 and 14. For intermediate pH values (between 8 and 10), thymolphthalein's color gradually changes from colorless to blue.

Michael has been splattered with disappearing ink. At first, the ink has a blueish color. But after a few minutes, the ink starts to fade!

A trick that takes the cake

A better natured trick is a frequent joke at birthday parties. A birthday cake full of candles is placed in front of a person—let's call this person Mike—to celebrate his birthday. After making a wish, he draws a big breath to blow out the candles. At first, he seems successful in blowing them out, but then, slowly, the candles sputter to life and soon, they are burning brightly again. No matter how many times Mike tries, he cannot seem to blow the candles out so they stay out. It's a birthday trick. Someone placed "magic" candles on the cake instead of normal birthday candles.

"Magic" candle (left); normal candle (right)

To understand how this trick works, let's see how regular candles work. In a regular candle, the wick is saturated with wax, so when you light the candle, the flame melts, vaporizes, and ignites the wax. This burning wax heats the wax of the main candle and "melts it. Then, the liquid wax rises in the wick and is vaporized by the flame.

The reason the lower part of the exposed wick does not burn—but the wax burns instead—is because the vaporizing wax cools it and prevents the wick from burning. This explains why the little part of the wick that burns is only at the tip, where the wax has completely evaporated.

After the flame has been blown out, it goes out because the draft blows away the wax vapor, which was the only hot part when the candle was lit.

In a "magic" candle, finely divided particles of metal, usually magnesium, have been added to the wick. These particles ignite easily and burn hot enough to ignite the wax vapor after the flame has been blown out. If you look up close, you can see these white-hot particles flashing off the wick.

Performing under pressure

Some tricks come in the form of a challenge. Two friends, Joe and Anne, set each other up. Anne asks Joe if he thinks he can put a peeled hard-boiled egg into a bottle that has a mouth slightly smaller than the diameter of the egg. When Joe tries to push the egg into the bottle, it breaks apart into a total mess. He gives up after trying with several more eggs, only to watch in amazement as Anne shows him how it can be done.

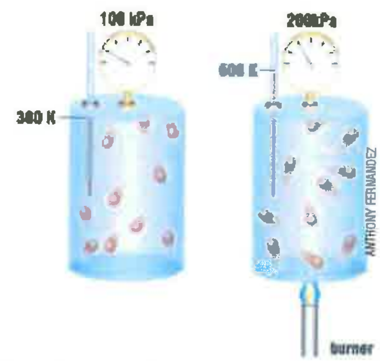


Figure 2. Schematic representation of Gay-Lussac's Law: The pressure of a given volume of gas increases when its temperature increases and the volume increase is proportional to the temperature increase. Also, the gas molecules move faster at higher temperatures.

First, she lights a small scrap of paper on fire and drops it into the bottle. After a moment, she places an egg on top of the bottle. The paper scrap burns for another second and goes out. Then, as if by magic, the egg slowly begins to move into the neck of the bottle and drops into the bottom of the bottle. Is it a tricked bottle, a tricked egg, or something else?

This trick can be explained with a basic understanding of the behavior of gases. Gases are made of molecules that are relatively far apart. Unlike solids and liquids, gases don't have a defined volume, so they

Unexpected but true! This hard-boiled egg goes through a bottle that has a mouth slightly smaller than the diameter of the egg. The reason? The pressure outside the bottle is slightly larger than the pressure inside the bottle.

expand to fill any container. If the temperature of a gas in a closed container is raised, the molecules move faster, and the pressure increases—a phenomenon called the Gay-Lussac's Law.

When Anne dropped the slip of burning paper into the bottle, it caused the temperature of the air inside to increase. Putting the egg in the bottle opening closed the bottle, so the pressure inside the bottle increased. Because the egg was just sitting on top of the bottle, it was lifted by the higher pressure inside, so some air escaped to equalize the pressure inside and outside the bottle.

After the fire went out, the air cooled back down, causing the air molecules to slow down, and the pressure inside dropped. The pressure outside the bottle—now higher than inside the bottle—started pushing the egg against the top of the bottle. Once the air inside the bottle cooled enough and the pressure inside dropped enough, the higher pressure outside pushed the egg through the bottle neck.

An illuminating trick

One final trick starts when two students, Sarah and Audrey go into a dark room. There is no light coming in through openings in the door or windows. Sarah puts a wintergreen candy into her mouth and crushes it with her teeth. She pulls her lips back so Audrey can see a beautiful flash of light each time a bit of the candy is crushed between Sarah's teeth. Although the light is pale, it definitely occurs when the wintergreen candy is crushed. Could it be some kind of magic? Or is it chemistry?

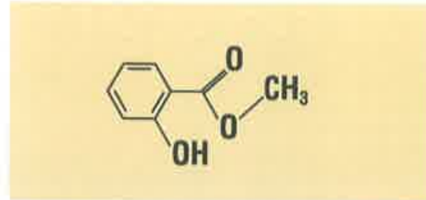
This is actually a combination of two effects called triboluminescence and fluorescence. Triboluminescence is the emission of light that results from crushing or pulling apart a material; fluorescence is the emission of light by a substance that has absorbed light of a different color.

When Sarah crushes the candy with her teeth, she shatters sugar crystals. As the sugar crystals are torn apart, they emit light by triboluminescence. For each piece of sugar crystal that is cracked, one section of the crystal ends up with more electrons, giving it a temporary negative charge, while the section that loses the electrons has a temporary positive charge.

Crushing a Wint-O-Green Lifesaver gives off a burst of blue light.

Immediately after these electrons move in the crystal, they rush back to their original positions. Some of them jump through the air in a crack, creating an electrical current that excites nitrogen molecules (N_2) in the air. In these excited nitrogen molecules, electrons move from their original energy levels to higher energy levels. A fraction of a second later, these electrons go back to their original energy levels and emit light. Most of this light is ultraviolet, which is invisible.

In addition to this ultraviolet light, there is also light produced by a chemical called methyl salicylate that



Methyl salicylate

gives wintergreen its flavor. This chemical produces light by fluorescence—it emits light after absorbing light of a different color. In this case, methyl salicylate absorbs the ultraviolet light produced by the sugar crystals and emits visible, blue light. So, the invisible light created by crushing the sugar crystals in the candy is changed into blue light by the methyl salicylate present in the candy.

Is it magic or chemistry?

Should we be disappointed that none of these tricks are magical? Not in the least! Maybe the fact that each of the unexpected effects in these tricks was due to basic chemistry should inspire us. After all, much of what we know and understand today is a result of someone observing something unexpected and looking for an explanation. In the end, demystifying everyday chemistry is where we find true magic!

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"Check out the *ChemMatters* video podcast on magic tricks at: www.acs.org/chemmatters !

The Quest for a Clean Drink

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

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:

$$-Fe-OH + H_2AsO_4^- \rightarrow -Fe-OAsO_3H^- + H_2O$$

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

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

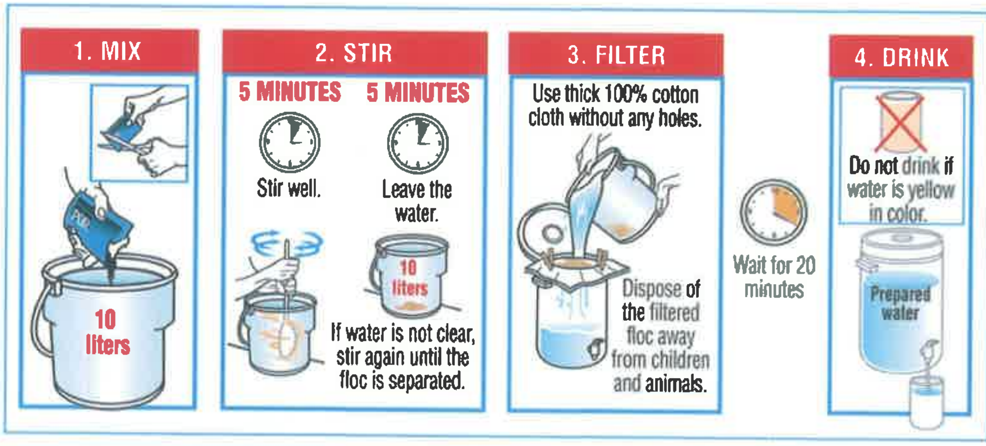
Front of the pouch containing arsenic-removing powder.

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.

ABUL K.M. MUNIR

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!

Christen Brownlee is a science writer at Johns Hopkins University School of Medicine's Division of Media Relations and Public Affairs, Baltimore, MD. Her article "Percy Julian: Rising Above Racism," appeared in the October 2007 issue of *ChemMatters*.