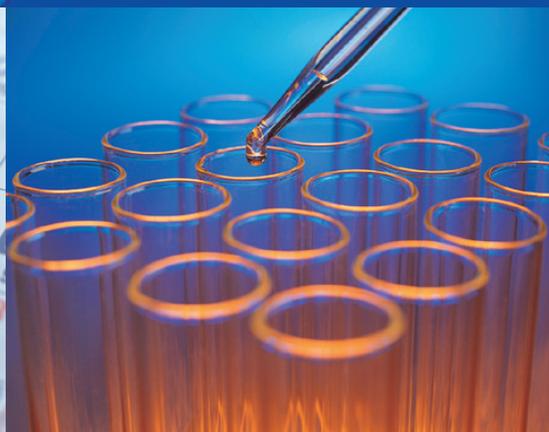




# PUREFLOW TechNotes

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## The Basics of Water Chemistry PART 1

by C.F. "Chubb" Michaud

**Summary:** Water chemistry is basic but, nonetheless, it's still chemistry. Some people shy away from trying to understand this subject because they feel it's over their heads. However, understanding the fundamentals of chemistry is necessary in order to grasp the full breadth of how certain aspects of water filtration work—especially ion exchange.

**Part 1** of this article will point out the basic ionization process and the relationships that exist between one species and another. It will also introduce the reader to the wealth of information available on the Periodic Table of Elements, the universal guide to chemical properties. **Part 2** will examine the guidelines for the proper use of a water analysis and point out some traps to avoid. **Part 3** will then describe how to use chemistry and ion exchange selectivity to solve certain treatment problems.

Mother Nature keeps an orderly house. There are less than 100 elements "in nature" and, by definition, they're all separate and distinct from one another. Copper, nickel, tin, zinc, sodium and oxygen are all elements.

Elements are made up of a balanced number of positive and negatively charged particles called protons (+) and electrons (-), which, along with neutrons (which are neutral), form an atom of that element. The atom is the smallest particle still identifiable as having the properties of the element. All elements are, being balanced with the same number of electrons and protons, neutral in charge.

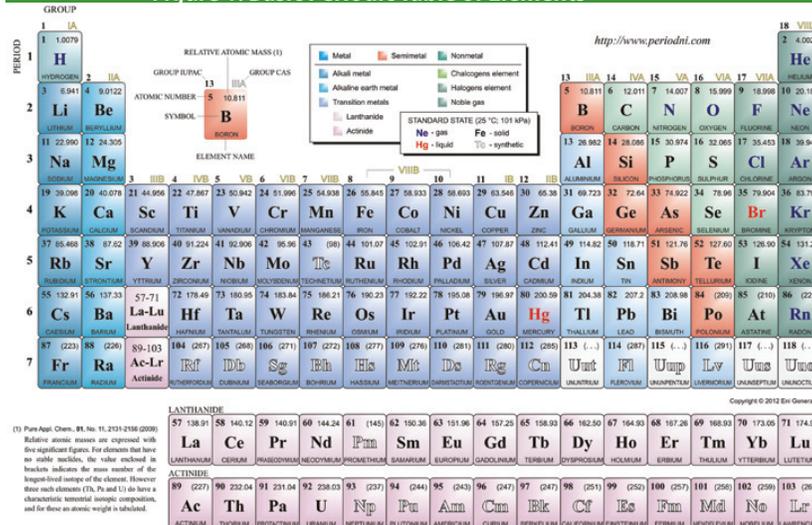
All elements can—and do—have different numbers of protons with a matching number of electrons. Hydrogen (H) has only one whereas Helium (He) has two. Lithium (Li) has three and so on all the way up to Uranium (U), which has 92. Plutonium (Pu), a manmade element that doesn't exist in nature, has 94 electrons and protons. The heaviest element known, Unihexium (Unh), also manmade, has 106. So, all numbers from 1 to 106 are accounted for. Each differs by only one proton and each is a totally separate substance with its own unique properties.



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Figure 1: Basic Periodic Table of Elements



We use the term Atomic Number (AN) to identify each of the elements and this number corresponds to the number of electrons of the element. These various elements are conveniently arranged on a chart we refer to as the Periodic Table of Elements (see Figure 1). The periodic table contains a wealth of information such as density, melting point, boiling point as well as valence, atomic weight and atomic number. Elements are grouped in “families” which have similarities and predictability of reaction.

Atomic weight (AW) represents the mass of an element and is the total of its protons and neutrons. It is possible to have elements of differing atomic weight, but with the same atomic number because the number of neutrons can vary. We refer to these variations as isotopes. For example, chlorine, which is element 17, can have 18 or 19 neutrons. Therefore, it has an atomic weight of 35 or 36. Since these two common isotopes exist in nearly the same percentage, we assign chlorine an atomic weight of 35.5.

The jagged line drawn through the chart in Figure 1 separates the metals from the non-metals (on the right). This helps you to determine how that substance will react with oxygen and subsequently how that compound will react with water. You might have noticed that boron (B), carbon (C), nitrogen (N), fluorine (F), silica (Si), phosphorous (P), sulfur (S), chlorine (Cl), arsenic (As), etc., on the non-metal side all seem to end up on the same side of the salt molecule. In other words, they are the acid formers whereas hydrogen, sodium, calcium, etc., are the base formers.

When subjected to heat in the presence of oxygen, most metals will form a metal oxide. The most common observation of this is rust, which is iron oxide. Lime is calcium oxide (CaO) and caustic is sodium oxide (Na<sub>2</sub>O). If we subscribe to the theory of a fiery creation, we can readily see where the heat came from. When a metal oxide is dissolved into water, a basic, or alkaline, solution is created, as can be seen in Reaction 1 in Figure 3. Non-metals, such as sulfur (S) and nitrogen (N) also form oxides, but when dissolved into water, they form acids. (See Reaction 2 in Figure 3.)

When elements combine to form compounds, nature preserves the laws of neutrality. Ammonia (NH<sub>3</sub>) is a gaseous compound made up of one atom of nitrogen and three atoms of hydrogen. Sodium chloride (NaCl) is a compound that’s a salt. What determines how many of *this* will react with how many of *that* to form so many of *those* also is fixed by the nature of the element.

## The Importance of Orbits

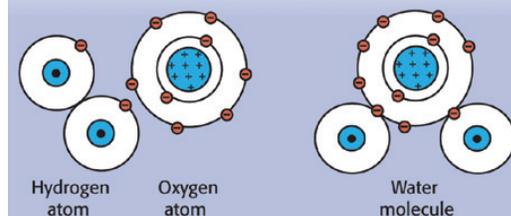
The electrons contained in each of the elements are arranged in electron orbits around the shell of the atom’s nucleus (center). There is more than one orbit—in fact, there are many. However, each orbit is filled with only a certain number of electrons and that number is more or less the same for all of the elements. Since the number of electrons differs by only one from one element to the next on the periodic chart, only the outermost orbit will contain a different number of electrons. This tiny difference determines many of the properties of that element and

the family to which it belongs. For instance, hydrogen, lithium, sodium and potassium all have only one electron in their outermost orbit. Magnesium, calcium and strontium each have two. Fluorine, chlorine, bromine and iodine—the halogen family—each have seven. On the far right of the Periodic Table, helium, neon, argon, krypton, xenon and radon form the inert gasses (non-reactive). Are we starting to get the picture of just how valuable the periodic table might be?

When electrons react to form compounds, they tend to go to a less reactive state. In other words, they try to imitate the “relaxed” state of the inert gasses by filling their outer orbits to completion. The innermost orbit needs only two electrons (or zero). The outermost generally wants eight. We can see from the periodic table that hydrogen, AN=1, has only one electron in its outer orbit. Oxygen with an AN=8 has two in its inner and six in the outer. To be “satisfied,” hydrogen will give up its electron and oxygen will pick it up. However, to satisfy the full demand of the oxygen, it will require two hydrogens to make the supreme sacrifice—thus, forming the basis of water. This is shown in Reaction 4 in Figure 3 as well as graphically with a depiction of the electron exchanged in Figure 2.

Other than the inert gasses, all elements will have from one to seven electrons in their outer orbits. They can either give them up or pick up additional ones to satisfy a full orbit. Sodium, which has one, will give that up to chlorine, which has seven. Thus both the chlorine and the sodium are satisfied and the resulting compound, NaCl, is neutral. Potassium has one and oxygen has six. Therefore, oxygen needs two and the resulting compound of potassium oxide is balanced as K<sub>2</sub>O.

Figure 2: How Water is Formed Selectively



## The Role of Salt and Water in Ion Exchange

When salt is dissolved in water, the two components of the salt separate. However, they don’t regain their original electron counts and therefore are no longer neutral. Since they now have either gained or lost electrons (which have a negative charge), they’ll have either a net positive (loss of electrons) or net negative (gain of electrons) charge. We call these charged particles ions. The positive ion is called a cation and a negative ion is called an anion. The number of electrons gained or lost by the element determines the strength of the charge. We call this charge its valence and we denote this by writing the symbol for the element or compound with a corresponding number to signify its ionic charge.

Thus, sodium is Na and its ion is Na<sup>+</sup>. Chlorine is Cl and its ion is Cl<sup>-</sup>.

Table 1 lists some of the more common elements found in tap water, the compound form most likely and its valence.

In general, all metals—even gold—will form oxides and, therefore, bases; Most non-metals will form acids. Acids neutralize bases to form salt and water. This is the most fundamental reaction in chemistry and perhaps, the most important one for ion exchange function. This reaction is shown in Reaction 3 in Figure 3.

Water, H<sub>2</sub>O, does not ionize as H<sup>+</sup> and O<sup>=</sup>. Instead, it becomes H<sup>+</sup> and OH<sup>-</sup>. We call the OH ion a hydroxyl ion and denote it with a negative one charge. These two ions are the backbone of the ion exchange demineralizer reaction, which is very simply a commercial application of the most basic law of chemistry shown, again, in Reaction 3 in Figure 3.

Although we commonly refer to sodium chloride (NaCl) as “salt”—which it is—it’s not the only salt. Any product of neutralization between an acid and a base will form a salt. Magnesium sulfate is a salt; potassium citrate is a salt. The names of salts usually have “-ide,” “-ite” and “-ate” endings.

## Selectivity

If we add two different soluble salts to water, say sodium carbonate and calcium chloride, we produce four different ions: Ca<sup>++</sup> (calcium), Na<sup>+</sup> (sodium), Cl<sup>-</sup> (chloride) and CO<sub>3</sub><sup>=</sup> (carbonate). The fact that the Ca<sup>++</sup> and CO<sub>3</sub><sup>=</sup> are more strongly charged is a hint that they’re more strongly attracted to one another. Being more strongly attracted means decreased solubility. Indeed, if we add enough Na<sub>2</sub>CO<sub>3</sub> (soda ash) to CaCl<sub>2</sub>, we do precipitate CaCO<sub>3</sub>, leaving a solution of salt (NaCl) and perhaps some excess Na<sub>2</sub>CO<sub>3</sub> and a slight amount of soluble CaCO<sub>3</sub>.

As shown by Reaction 5 in Figure 3, certain elements or compounds in water can be made to undergo specific selective reactions and these reactions are predictable to some degree according to the element’s family association in the periodic table. Divalent ions (those with a double positive charge) such as calcium and magnesium, will react with soap and cause “bathtub ring.” They also will react with the carbonate ion to form scale in pipes and heaters. Although we could precipitate these salts with the addition of carbonate ions (see Reaction 5 in Figure 3), we have no easy way to remove the resulting solid. Likewise, we can neutralize an acid with a base (see Reaction 3 in Figure 3), but we end up with a soluble salt in our water.

With ion exchange resins, only the exchangeable ion is soluble. The counter ion, which is the resin bead itself, is not. This makes the separation after the exchange very easy. In the case of a softener, the resin has an exchangeable Na<sup>+</sup>. The hardness (Ca<sup>++</sup> and Mg<sup>++</sup>) combined with the resin forms a very strong bond. The water, minus the hardness, passes on through because the resin is retained in the exchange column. Sodium (or potassium) replaces the hardness on an equivalent basis. This means that it will take two sodium ions from the exchange bead to replace a single calcium or magnesium ion.

In the case of demineralization, both the cations and the anions must be exchanged. This is done by using two different resins regenerated with acid and caustic respectively. The water passes through the cation exchanger first where the positive ions (cations) are exchanged for hydrogen ions (H<sup>+</sup>). (See Reaction 6 in Figure 3.) The acid solution is then passed through an anion exchanger where the acid is neutralized by the exchange of the acid ion (Cl<sup>-</sup>) for the hydroxyl (OH<sup>-</sup>) ion. (See Reaction 7 in Figure 3.)

## Conclusion

The periodic table of the elements places all elements into families that help us predict properties and determine similarities. We have shown that there is a preferred coupling of certain elements to form reactions (such as CaCO<sub>3</sub> precipitation) that lead us to methods of removing those elements from water. This can be done either selectively (such as in softening) or completely (as in demineralization).

### References

1. Dictionary of Chemistry, McGraw-Hill, New York, 1994.
  2. Kunin, Robert, Ion Exchange Resins, Krieger Publishing, New York, 1972.
  3. Wachinski, A.M., and J.E. Etzel, Environmental Ion Exchange, Lewis Publishers, New York, 1997.
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Table 1

### Common Elements Found in Tap Water

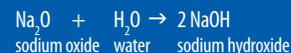
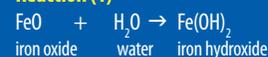
Element	Ionic Form	Valence
Calcium	Ca <sup>++</sup>	+2
Magnesium	Mg <sup>++</sup>	+2
Sodium	Na <sup>+</sup>	+1
Potassium	K <sup>+</sup>	+1
Aluminum	Al <sup>+++</sup>	+3
Iron	Fe <sup>++</sup>	+2 (ferrous)
	Fe <sub>2</sub> O <sub>3</sub>	0 (ferric, rust)
Manganese	Mn <sup>+++</sup>	+2 (manganous)
Fluoride	F <sup>-</sup>	-1
Chloride	Cl <sup>-</sup>	-10
	Cl <sup>-</sup>	-1 (free chlorine)
Oxygen	OH <sup>-</sup>	-1 (hydroxyl)
Nitrogen	NO <sub>3</sub> <sup>-</sup>	-1 (nitrate)
	NO <sub>2</sub> <sup>-</sup>	-1 (nitrite)
	NH <sub>4</sub> <sup>+</sup>	+1 (ammonia)
Sulfur	SO <sub>4</sub> <sup>=</sup>	-2 (sulfate)
	SO <sub>3</sub> <sup>=</sup>	-2 (sulfite)
	S <sup>=</sup>	-2 (sulfide)
Carbon	HCO <sub>3</sub> <sup>-</sup>	-1 (bicarbonate)
	CO <sub>3</sub> <sup>=</sup>	-2 (carbonate)
Silica	SiO <sub>2</sub>	0 (colloidal)
	H <sub>2</sub> SiO <sub>3</sub>	<-1 (weakly charged acid)

Figure 3

### Reactions

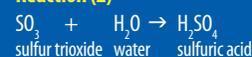
When a metal is dissolved in water, a basic, or alkaline solutions is created:

#### Reaction (1)



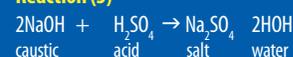
Non-metals like sulfur and nitrogen also form oxides, but when dissolved into water, they form acids:

#### Reaction (2)



Acids neutralize bases to form salt and water:

#### Reaction (3)

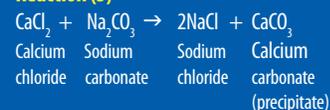


The formation of water is expressed as:

#### Reaction (4)

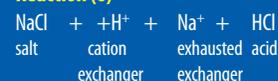


#### Reaction (5)



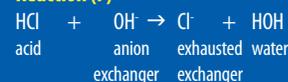
Ion exchange with cation exchanger:

#### Reaction (6)



Ion exchange with anion exchanger:

#### Reaction (7)



Chubb Michaud is the CEO and Technical Director of Systematix Company (founded in 1982) of Buena Park, CA. He has over 35 years of field experience in water and fluid treatment applications and system design and he holds several U.S. Patents on ion exchange processes. Michaud has served on the Water Quality Association Board of Directors and Board of Governors. He is a WQA Certified Water Specialist Level VI. He is currently on the Board of Directors of the Pacific WQA where he has chaired the Technical and Education Committees for the past 12 years. Michaud has received numerous awards in recognition of his technical contributions to the industry. He was inducted into the PWQA Hall of Fame in 2007. He is a founding member of the Technical Review Committee for Water Conditioning and Purification Magazine and has authored over 100 technical publications and papers.

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- Aristotle



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