

## Chapter 1

# Introducing Inorganic Chemistry

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### *In This Chapter*

- ▶ Getting familiar with basic concepts in chemistry
  - ▶ Building your knowledge of chemical bonding
  - ▶ Traveling across the periodic table
  - ▶ Delving into details with special topics
  - ▶ Counting by tens: products, prizes, instruments, and experiments
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**I**norganic chemistry is a practical science. By studying it, you become familiar with the intricate working of processes and materials — from how silicon works in a semiconductor to the reason why steel is stronger than iron. Inorganic chemistry is important for civilization and technological development.

The science of inorganic chemistry covers a great deal of material; in short, it's the chemistry of everything you see around you. Inorganic chemistry explores and defines laws that atoms follow when they interact, including trends in how they react, characteristics they possess, and the materials they make. It may seem daunting at first to think about how many possibilities there are in the science of inorganic chemistry. Fortunately, each new concept builds on another concept in a very logical way.

This chapter explains what to expect when reading this book and should help you find the right section to guide you through your study of inorganic chemistry.

## *Building the Foundation*

Before diving into the particular details of inorganic chemistry, it's helpful to understand some of the prominent ideas in general chemistry that are useful to further appreciate inorganic chemistry.

## What difference does it make?

It's important to be able to distinguish between inorganic and organic chemistry. Organic chemistry deals primarily with the reaction of carbon, and its many interactions. But inorganic chemistry deals with all of the other elements (including carbon, too), and it details the various reactions that are possible with each of them. There are a huge number of examples in everyday life that can be described by inorganic

chemistry — for example, why metals have so many different colors, or why metal compounds of the same metal can have such varying colors too, like the ones that are used and pigments in paints. It can help to explain how alloys form and what alloys are stronger than others. Or why a dentist uses an acid to open the pores in your teeth before applying an adhesive to make a filling hold fast.

Chemistry is a science of change. It looks at how individual atoms interact with each other and how they are influenced by their environment. We start by explaining what atoms look like, and we describe details of their structure. This is important because the way that the atom is made up determines how reactive that atom is, and as a result of the activity, it can be used by a chemist to make materials. After you have these basics down, you are able to understand the physical properties of many materials based on what atoms they are made from, and why they are made using those specific atoms.

Stemming from this basis of general chemistry we then deal with the specifics of inorganic chemistry. This includes an understanding of approximately 100 atoms that are of practical interest to chemists. To simplify this, inorganic chemistry is understood according to some general trends based on atomic structure that affect the reactivity and bonding of those atoms. This is quite different from the study of organic chemistry that deals with the reactions of just a few atoms, such as carbon, oxygen, nitrogen, and hydrogen. But there is an overlap between inorganic chemistry and organic chemistry in the study of organometallic compounds.

## *Losing your electrons*

In chemical reactions, follow the electrons because electrons hold the key to understanding why reactions take place. Electrons are negatively charged, mobile, and can move from atom to atom; they can be stripped from atoms, too. Atoms are always trying to have just the right amount of electrons to keep stable. If a stable atom has cause to lose or gain an electron, it becomes reactive and starts a chemical process.

The nucleus of an atom has a positive force that attracts electrons. This comes from protons within the nucleus that influence electrons to orbit around the nucleus. As you progress in atomic size, one proton at a time, there is room for one more electron to orbit around the atom.

There are periodic trends that can be seen in the periodic table, the first of which deals with the stability of atoms according to the number of outer electrons in the atom. This is known as *valency*, and it can be used to show why some atoms are more reactive than others. There are many more periodic trends that are associated with the electrons around the atoms, and you can find more examples in Chapter 2.

Take a stable atom, such as iron, for example. Imagine that you remove an electron from iron; it now has a different reactivity. This is known as oxidation chemistry, and it's the focus of Chapter 3. The chemistry of oxidation tracks how electrons are gained or lost from molecules, atoms, or ions. When an electron is lost, the molecule, atom, or ion is said to have an increased oxidation state, or is considered *oxidized*. When the opposite occurs and a molecule, atom, or ion gains an electron, its oxidation state is *reduced*.

Originally named from the common involvement of oxygen molecules in these types of reactions, chemists now realize that oxidation and reduction reactions (sometimes referred to as redox chemistry) can occur among molecules, atoms, and ions without oxygen.

## *Splitting atoms: Nuclear chemistry*

Another area of general chemistry with which you should be familiar is the study of radioactivity, or nuclear chemistry. Specifically, nuclear chemistry deals with the properties of the nucleus of the atoms; that's why it is called nuclear chemistry.

As you progress through the periodic table each successive atom has one more proton and neutron compared with the previous atom. The protons are useful for attracting electrons, and the neutrons are useful for stabilizing the nucleus. When there is an imbalance between the two nuclear particles (proton and neutron), the nucleus becomes unstable, and these types of atoms are called *isotopes*. If they are radioactive, they are called *radioisotopes*, and they can be useful, for example, in medical applications.

Although you may immediately think about nuclear reactors for energy, or nuclear bombs and their incredible devastation, concepts in nuclear chemistry are applied for many other, less dramatic purposes, one such example is carbon dating of ancient materials (see Chapter 4).

The nuclear processes can affect the properties of the atoms, and this can have an effect on the properties of materials that are made with those atoms. For example, there is often a lot of heat generated by radioactive atoms, and this heat can affect material properties. Did you know that much of the potassium in our body is in the form of a radioactive isotope? This accounts for some of the heating within our own bodies (see Chapter 11).

## Changing pH

In Chapter 5, we explain the basics of acids and bases, including how the pH scale was developed to quantify the strength of different acids and bases. It's a simple system that ranges in value from pH 1 to pH 14.

Acids have low pH values in the range of pH 1 to pH 7. Bases have high pH values that range from pH 7 to pH 14. In the middle there is pH 7, and this is considered neutral pH, which is also the pH of water. And subsequently is nearly the same pH as blood, demonstrating how important water is to us.

The pH of blood is highly sensitive; if it changes too much, we can get very sick. The preferred range for maintaining stable health is from pH 7.35 to pH 7.45, making blood slightly basic. This simple fact alone highlights the importance of green foods in your diet; they're alkalizing in your body and help maintain a healthy *you*.

Chemists have been working for many years to sort out what specifically makes something an acid or a base. Through this work, multiple definitions of acids and bases have been proposed. As we explain in Chapter 5, there are two important models for examining acid-base chemistry:

- ✓ **Brønsted-Lowry model:** In this model, an acid is a proton (H) donor, whereas a base accepts hydroxyl groups (OH molecule).
- ✓ **Lewis model:** In this model, acids are electron pair acceptors and bases are electron pair donors.

Earlier we said you needed to track the electrons to understand what is happening in various chemical reactions. By using the Lewis model that deals with electron pairs, you can get a good understanding of how reactions occur, by tracking the electron pairs and seeing where they come and go.

It's important to understand the distinction between these two models. The Brønsted-Lowry model was developed when acids and bases were thought to work in aqueous solvents. As a result, it deals only with hydrogen and hydroxyl groups. On the other hand, the Lewis model was developed to show what happens when water isn't the solvent, so it deals with electrons instead.

## Getting a Grip on Chemical Bonding

Part II delves into how bonding occurs between atoms, and how to distinguish between the types of bonds that are created. Bonding between atoms is important for all scientists to understand because it affects the properties and applications of materials in profound ways. In practice, there are about

100 atoms that are stable enough to form bonds, but there are only three types of bonding known:

- ✓ **Covalent:** *Covalent bonding* stems from the sharing of electrons and the overlap and sharing of electrons orbitals between atoms. Covalent bonds are very strong as a result of this. Covalent bonds have *directionality*, or a preference for a specific orientation relative to one another, this results in molecules of interesting and specific shapes. As a result, elaborate molecules can be made that have specific structures and symmetry, which we describe in Chapter 7.
- ✓ **Ionic:** *Ionic bonding* occurs when atoms donate or receive electrons rather than share them. One ion is positively charged, and it's balanced by an ion that is negatively charged; they're known as the *cation* and the *anion*, respectively. Each ion is treated as if it's a spherical entity with no distortion of the electron orbital. See more information in Chapter 8.
- ✓ **Metallic:** *Metallic bonds* are similar to ionic bonds, so we describe them both in Chapter 8. The main difference is that in metallic bonds the electrons are shared among all the other atoms in the metal materials. This is known as the delocalization of electrons because they are not found locally around one particular atom. This gives rise to many of the properties of metals.

There aren't strict lines between each type of bond, and sometimes the way atoms bond together is a combination or mixture of more than one bond type. Throughout Part II we explain each of the bond types individually; then in Chapter 9 we will look at how they each influence the formation of molecules known as *coordination complexes*, which include metallic compounds and connecting molecules called *ligands*.

## Traveling Across the Periodic Table

There are over 100 known atoms, and it can be overwhelming to try to remember each and every one of them. This is what chemists tried to do before the *periodic table* was created. In Part III, you learn about this important chart that organizes the elements according to their similarities in structure and reactivity. The simplicity and beauty of the periodic table makes it easier to find and compare elements against each other. If the familiar expression “a picture is worth a thousand words” was used to describe inorganic chemistry, then the picture that best describes it is the periodic table. We've devoted the chapters in Part III to exploring the periodic table from one end to the other and describing the key characteristics of each group.

Here you can see what the periodic table looks like. Notice how there are 18 groups from left to right as seen at the top. And there are seven periods going from top to bottom as shown on the left side of the table.

PERIODIC TABLE OF THE ELEMENTS

Period	Group																	
	1																	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg	3	4	5	6	7	8	9	10	11	12	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

  

Periodic Table Key														
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

  

X Synthetic elements	X Liquids or melt at close to room temp.	X Solids	X Gases	Alkali metals	Alkali earth metals	Transition metals	Other metals	Metalloids	Other non metals
				Halogens	Noble gases	Lanthanides & actinides			

**Figure 1-1:**  
The periodic  
table of the  
elements.

## Hyping up hydrogen

Hydrogen is one of the most abundant elements in the universe, and Chapter 10 explains the unique and important properties. This element sits at the upper-left corner of the periodic table and serves as the first step in a long line of stepping stones for you to travel across the periodic table. Some points to know about hydrogen include:

- ✔ Hydrogen is highly reactive. It lacks one electron in the outer orbital to make it stable, so it has a very reactive valency. This makes it explosive, and for this reason it's usually found as  $H_2$  — two hydrogen atoms bonded together. Because each hydrogen shares the electron, it pacifies the atom.
- ✔ Hydrogen is used in a technique called *nuclear magnetic resonance*. This is important because it can be used to elaborate exactly where hydrogen atoms are within a molecule so it can show the structure of the molecule.
- ✔ Hydrogen can bond with nearly every single atom on the periodic table, making it a versatile atom.

## *Moving through the main groups*

The most common elements are found in the *main groups* of the periodic table. The main group elements comprise many of the materials we know from everyday experience.

The main group elements include the Group 1 and Group 2 elements on the left side of the table along with Groups 13, 14, 15, 16, 17, and 18 on the right side of the table. The most reactive is on the left side; The most inert and calm reside on the far right. As you might expect, the middle atoms have mixed qualities between these two extremes.

A few of the main group elements have specific qualities recognized by chemists. For example:

- ✓ **Alkali and alkaline earth metals:** The elements in the first two columns of the periodic table (excluding hydrogen) are formally known as the alkali and alkaline earth metals, or s-block elements. They are highly reactive and often explosive elements, but also extremely important in biology. Compounds made with Group 1 and 2 elements are often referred to as salts; skip ahead to Chapter 11 to find out why.
- ✓ **Noble gases:** The elements in the far right column of the periodic table are the noble gases and are mirror opposites of the alkali and alkaline earth metals. Instead of being reactive, for the most part they are inert, or nonreactive. The noble gases have no need for more electrons, so they generally don't react with other atoms to gain, give, or share electrons. There are some exceptions, however, because the gases of argon, krypton, and xenon can form compounds with fluorine. More of this can be found in Chapter 12.

The rest of the main group elements, called p-block elements, contain the atoms that are associated with life and living matter, including carbon, oxygen, and nitrogen. More information can be found in Chapters 12 and 17.

## *Transitioning from one side of the table to another*

In the center of the periodic table are the elements that transition from the s-block main group elements to the p-block main group elements. These elements are called the *transition metals* or d-block elements. The transition metals act as cushion between the highly reactive elements on the far left and the less reactive elements on the right.

These elements are important for industry and help in the synthesis of organic molecules and medicinal compounds. You can find a number of them in the catalytic converter of your car, for example.

Transitional metals are important because they're used as catalysts in the chemical industry. They're often reactive atoms, and under the appropriate conditions can complete reactions and make large amounts of molecules with a very specific size and shape. Much of the plastic materials that are in use today are made possible on such a grand and industrial scale thanks to the development of catalysis using transition metals. More information about catalysis can be found in Chapter 16. Catalysts make short work of specific chemical reactions; they have the ability to create a product faster, and with less energy.

Some of the reactions that take place in the body do so because of transition metals. For example, the oxygen that we breathe is carried around the body using a compound that has iron at the center. This is called hemoglobin. But the other transition metals can play important roles in the body also, for more information see Chapter 17.

Many transition metals are used in everyday materials that we use regularly. These metals often have interesting electronic and magnetic properties, and because of this they're commonly used in electronic devices. But at the nanoscale (that being the very small scale), they have some other very interesting properties that can be harnessed. For more information about nanotechnology, check out Chapter 19.

## *Uncovering lanthanides and actinides*

Buried deep inside the transition metals are two more groups with important, unique characteristics — lanthanides and actinides. They are unique because they use orbital shells that aren't important to the rest of the periodic table. The chemistry of these materials are not fully understood yet, because some are rare and hard to find, whereas others are radioactive and dangerous to work with. For more information about these elements, see Chapter 14.

## *Diving Deeper: Special Topics*

In Part IV, you get the opportunity to explore some of the more specialized subfields of inorganic chemistry. Each chapter introduces you to how inorganic chemistry is used in a specific way, such as increasing reaction speed (catalysis), or capturing energy from the sunlight (in a chemical reaction called photosynthesis), and building smaller and smaller computer devices. In each chapter, we only brush the surface of these fascinating special topics. But you have enough of the working tools to further your own detailed study of these topics when you want.



## *Bonding with carbon: Organometallics*

In Chapter 14, we introduce the field of *organometallic chemistry*. As the name suggests, it deals with the chemistry of carbon-containing (or organic) molecules called *ligands* that bond with metals to form organometallic compounds. Organometallic chemistry combines some aspects of organic chemistry with some aspects of metallic chemistry, and the results are compounds with some unique traits, such as:

- ✓ The effect of the ligands can be so significant that the colors can be bright blue, red, or green, depending on what ligands are used and where they are placed around the metal center. Atoms with the same metal center can have very bright and brilliant color changes with the addition of different ligands. Many of these compounds are used as pigments in paints.
- ✓ Most of the organometallic compounds are made with transition metals as the metal center. These metals can have differing magnetic properties depending on the oxidation states, which can be controlled by the placement and type of ligands that are used around the metal.
- ✓ Organometallic compounds are often used as catalysts. Because they can have very specific geometries, they can make very specific chemical reactions occur.

## *Speeding things up: Catalysts*

Imagine how much more work you could get done if you found a short cut that's faster and has greater precision in producing results. In chemistry this is possible thanks to catalysis. *Catalysis* is the chemistry of making things happen faster, or making them happen with less required energy, or both. Catalysis is carried out by chemicals that are called *catalysts*. A catalyst makes light work out of heavy-duty chemistry. Catalysts are important because they allow for the quick and cheap production of strong and durable materials, such as plastics.

## *Inside and out: Bio-inorganic and environmental chemistry*

You don't just find examples of inorganic chemistry in the laboratory or in industry; you can also find them inside yourself or around your environment. For instance, the oxygen you're inhaling right now is being transported

around your body by an iron compound inside a large organometallic molecule called *hemoglobin*. In Chapter 17, we explain how and why this works. Other examples of bio-inorganic chemistry that are described in Chapter 18 include:

- ✔ **Photosynthesis:** The chemical reactions involved in photosynthesis transform sunlight energy and carbon dioxide molecules into sugar, water, and oxygen molecules.
- ✔ **Nitrogen fixation:** Some bacteria perform chemical reactions that capture atmospheric nitrogen and fix it so that it can be absorbed by organisms (usually plants) through a series of inorganic chemical reactions. The importance of this chemistry can't be over emphasized. Nitrogen is extremely important to living matter, and nature has developed efficient methods using enzymes in bacteria to work with nitrogen. Science has only recently created similar tools to do so, albeit much more crude than the way that nature does.
- ✔ **Enzymes:** Enzymes are proteins that act as catalysts for important functions within your body. Take for example, lactase — the enzyme that's used to help with the digestion of milk. Some people are lactose intolerant because they lack this enzyme, but they can overcome this by consuming a pill that contains lactase.

## *Solid-state chemistry*

Solid-state chemistry is based on the study of atoms that combine to build solid structures, or crystals. In Chapter 18, you learn how solid-state chemists describe the shape of crystal structures and how this determines the size and shape of the unit cell, which is then used to characterize the many different forms that solid structures take. For example:

- ✔ **Simple crystal structures:** Simple crystal structures are composed of atoms that are positioned on the edges of the unit cell.
- ✔ **Binary crystal structures:** Binary crystal structures are made of two type of atoms in the crystal, such as NaCl (table salt), for example.
- ✔ **Complex crystal structures:** These are more involved than the other examples because they can have more than two different types of atoms present.

One of the most important advances in solid state chemistry is the development of silicon-based materials. The Silicon Valley is where the semiconductor industry was born; scientists worked very hard to learn how to purify silicon and arrange the silicon atoms in such a way that they can be used to make a computer chip. At the heart of every single computer, and most electronic devices, is silicon. Just look around you and imagine a world without silicon, it would be a very different place.

## *Nanotechnology*

In the final chapter of Part IV, we tackle a very new and exciting field called nanotechnology. In this area of study, the size and shape of materials is often of paramount importance. At the size scale of living matter (bacteria are 20 nanometers (nm) in size, DNA is 1-2 nm wide) inorganic chemists can make exquisite materials with near-atomic precision. The advantage of nanotechnology is realized in many different applications; for example, it can be used to enhance catalytic processes, in biomedical applications, and to enhance the mechanical properties of bulk materials.

Nanotechnology is one of the most recent developments to arise from the sciences. It was developed only a couple of decades ago, but already the number of scientific publications and discoveries has been staggering. One of the unique features of this area is that it is important not just for the development of chemistry research, but also physics and biology, too. For this reason many new developments are occurring due to collaborations among researchers of physics, chemistry, and biology. Some of these include foldable electronics, anti-cancer treatments, ever smaller computers, and new methods of water filtration, to name just a few.

Nature has been working at the nanoscale for eons, only now can humankind begin to work at this scale, too. This final chapter gives a brief introduction to the major findings and applications of nanotechnology, but in no way gives full justice to the vast amount of work being carried out in this field. We hope that upon reading Chapter 19 you agree that the future is nano, and that inorganic chemistry plays a vital role in the continued development of this technology.

## *Listing 40 More*

The last part of this book (Part V and the Part of Tens) gives you some non-technical information about inorganic chemistry. We start right at home by listing some of the common household products that involve inorganic chemical reactions, or inorganic compounds in Chapter 20. These household items may come in handy if you want to try out any of the ten experiments listed in Chapter 23.

Chapter 21 describes ten chemists (or teams of chemists) who have played an important role for inorganic chemistry and who were recognized for their achievements by receiving the Nobel Prize. Finally, Chapter 22 describes ten of the more useful and interesting techniques used in inorganic chemistry research.

