

- Locate transition metals on the periodic table
- Describe typical physical and chemical properties of the transition metals

Transition metals are defined as those elements that have (or readily form) partially filled  $d$  orbitals. As shown in Figure 2.1.2, the  $d$ -block elements in groups 3–11 are transition elements. The  $f$ -block elements, also called *inner transition metals* (the lanthanides and actinides), also meet this criterion because the  $d$  orbital is partially occupied before the  $f$  orbitals. The  $d$  orbitals fill with the copper family (group 11); for this reason, the next family (group 12) are technically not transition elements. However, the group 12 elements do display some of the same chemical properties and are commonly included in discussions of transition metals. Some chemists do treat the group 12 elements as transition metals.



The *d*-block elements are divided into the first transition series (the elements Sc through Cu), the second transition series (the elements Y through Ag), and the third transition series (the element La and the elements Hf through Au). Actinium, Ac, is the first member of the fourth transition series, which also includes Rf through Rg.

B = Solids										Hg = Liquids										Kr = Gases										Pm = Not found in nature																																																																																																																																																					
<div>1<div>H1.00794</div></div>										<div>2<div>He4.00260</div></div>																																																																																																																																																																									
<div>3<div>Li6.941</div></div>										<div>4<div>Be9.012182</div></div>																																																																																																																																																																									
<div>11<div>Na22.989770</div></div>										<div>12<div>Mg24.3050</div></div>																																																																																																																																																																									
<div>19<div>K39.0983</div></div>										<div>20<div>Ca40.078</div></div>										<div>21<div>Sc44.955910</div></div>										<div>22<div>Ti47.867</div></div>										<div>23<div>V50.9415</div></div>										<div>24<div>Cr51.9961</div></div>										<div>25<div>Mn54.938049</div></div>										<div>26<div>Fe55.845</div></div>										<div>27<div>Co58.933200</div></div>										<div>28<div>Ni58.6934</div></div>										<div>29<div>Cu63.545</div></div>										<div>30<div>Zn65.39</div></div>										<div>31<div>Ga69.723</div></div>										<div>32<div>Ge72.61</div></div>										<div>33<div>As74.92160</div></div>										<div>34<div>Se78.96</div></div>										<div>35<div>Br79.904</div></div>										<div>36<div>Kr83.80</div></div>									
<div>37<div>Rb85.4678</div></div>										<div>38<div>Sr87.62</div></div>										<div>39<div>Y88.90585</div></div>										<div>40<div>Zr91.224</div></div>										<div>41<div>Nb92.90638</div></div>										<div>42<div>Mo95.94</div></div>										<div>43<div>Tc(98)</div></div>										<div>44<div>Ru101.07</div></div>										<div>45<div>Rh102.90550</div></div>										<div>46<div>Pd106.42</div></div>										<div>47<div>Ag107.87</div></div>										<div>48<div>Cd112.411</div></div>										<div>49<div>In114.818</div></div>										<div>50<div>Sn118.710</div></div>										<div>51<div>Sb121.760</div></div>										<div>52<div>Te127.60</div></div>										<div>53<div>I126.90447</div></div>										<div>54<div>Xe131.29</div></div>									
<div>55<div>Cs132.90545</div></div>										<div>56<div>Ba137.327</div></div>										<div>71<div>Lu174.967</div></div>										<div>72<div>Hf178.49</div></div>										<div>73<div>Ta180.9479</div></div>										<div>74<div>W183.84</div></div>										<div>75<div>Re186.207</div></div>										<div>76<div>Os190.23</div></div>										<div>77<div>Ir192.217</div></div>										<div>78<div>Pt195.078</div></div>										<div>79<div>Au196.96655</div></div>										<div>80<div>Hg200.59</div></div>										<div>81<div>Tl204.3833</div></div>										<div>82<div>Pb207.2</div></div>										<div>83<div>Bi208.98038</div></div>										<div>84<div>Po(209)</div></div>										<div>85<div>At(210)</div></div>										<div>86<div>Rn(222)</div></div>									
<div>87<div>Fr(223)</div></div>										<div>88<div>Ra(226)</div></div>										<div>103<div>Lr(262)</div></div>										<div>104<div>Rf(261)</div></div>										<div>105<div>Db(262)</div></div>										<div>106<div>Sg(263)</div></div>										<div>107<div>Bh(262)</div></div>										<div>108<div>Hs(265)</div></div>										<div>109<div>Mt(266)</div></div>										<div>110<div>Ds(269)</div></div>										<div>111<div>Rg(272)</div></div>										<div>112<div>Cn(277)</div></div>										<div>113<div>Uut(277)</div></div>										<div>114<div>Uuq(277)</div></div>										<div>115<div>Uup(277)</div></div>										<div>116<div>Uuh(277)</div></div>										<div>118<div>Uuc(277)</div></div>																			
<div>57<div>La138.9055</div></div>										<div>58<div>Ce140.116</div></div>										<div>59<div>Pr140.50765</div></div>										<div>60<div>Nd144.24</div></div>										<div>61<div>Pm(145)</div></div>										<div>62<div>Sm150.36</div></div>										<div>63<div>Eu151.964</div></div>										<div>64<div>Gd157.25</div></div>										<div>65<div>Tb158.92534</div></div>										<div>66<div>Dy162.50</div></div>										<div>67<div>Ho164.93032</div></div>										<div>68<div>Er167.26</div></div>										<div>69<div>Tm168.93421</div></div>										<div>70<div>Yb173.04</div></div>																																																	
<div>89<div>Ac232.0381</div></div>										<div>90<div>Th232.0381</div></div>										<div>91<div>Pa231.03588</div></div>										<div>92<div>U238.0289</div></div>										<div>93<div>Np(237)</div></div>										<div>94<div>Pu(244)</div></div>										<div>95<div>Am(243)</div></div>										<div>96<div>Cm(247)</div></div>										<div>97<div>Bk(247)</div></div>										<div>98<div>Cf(251)</div></div>										<div>99<div>Es(252)</div></div>										<div>100<div>Fm(257)</div></div>										<div>101<div>Md(258)</div></div>										<div>102<div>No(259)</div></div>																																																	

The *f*-block elements are the elements Ce through Lu, which constitute the lanthanide series (or lanthanoid series), and the elements Th through Lr, which constitute the actinide series (or actinoid series). Because lanthanum behaves very much like the lanthanide elements, it is considered a lanthanide element, even though its electron configuration makes it the first member of the third transition series. Similarly, the behavior of actinium means it is part of the actinide series, although its electron configuration makes it the first member of the fourth transition series.

### ✓ Example 2.1.1: Valence Electrons in Transition Metals

Review how to write electron configurations, covered in the chapter on electronic structure and periodic properties of elements. Recall that for the transition and inner transition metals, it is necessary to remove the *s* electrons before the *d* or *f* electrons. Then, for each ion, give the electron configuration:

- cerium(III)
- lead(II)
- $\text{Ti}^{2+}$
- $\text{Am}^{3+}$
- $\text{Pd}^{2+}$

For the examples that are transition metals, determine to which series they belong.

#### Solution

For ions, the *s*-valence electrons are lost prior to the *d* or *f* electrons.

- $\text{Ce}^{3+}[\text{Xe}]4f^1$ ;  $\text{Ce}^{3+}$  is an inner transition element in the lanthanide series.
- $\text{Pb}^{2+}[\text{Xe}]6s^25d^{10}4f^{14}$ ; the electrons are lost from the *p* orbital. This is a main group element.
- titanium(II)  $[\text{Ar}]3d^2$ ; first transition series
- americium(III)  $[\text{Rn}]5f^6$ ; actinide
- palladium(II)  $[\text{Kr}]4d^8$ ; second transition series

### ? Exercise 2.1.1

Check Your Learning Give an example of an ion from the first transition series with no *d* electrons.

#### Answer

$\text{V}^{5+}$  is one possibility. Other examples include  $\text{Sc}^{3+}$ ,  $\text{Ti}^{4+}$ ,  $\text{Cr}^{6+}$ , and  $\text{Mn}^{7+}$ .

### 📌 Uses of Lanthanides in Devices

Lanthanides (elements 57–71) are fairly abundant in the earth's crust, despite their historic characterization as rare earth elements. Thulium, the rarest naturally occurring lanthanoid, is more common in the earth's crust than silver ( $4.5 \times 10^{-5}\%$  versus  $0.79 \times 10^{-5}\%$  by mass). There are 17 rare earth elements, consisting of the 15 lanthanoids plus scandium and yttrium. They are called rare because they were once difficult to extract economically, so it was rare to have a pure sample; due to similar chemical properties, it is difficult to separate any one lanthanide from the others. However, newer separation methods, such as ion exchange resins similar to those found in home water softeners, make the separation of these elements easier and more economical. Most ores that contain these elements have low concentrations of all the rare earth elements mixed together.

The commercial applications of lanthanides are growing rapidly. For example, europium is important in flat screen displays found in computer monitors, cell phones, and televisions. Neodymium is useful in laptop hard drives and in the processes that convert crude oil into gasoline (Figure 2.1.3). Holmium is found in dental and medical equipment. In addition, many alternative energy technologies rely heavily on lanthanoids. Neodymium and dysprosium are key components of hybrid vehicle engines and the magnets used in wind turbines.

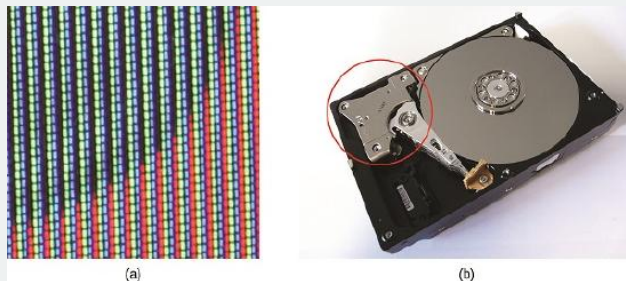


Figure 2.1.3: (a) Europium is used in display screens for televisions, computer monitors, and cell phones. (b) Neodymium magnets are commonly found in computer hard drives. (credit b: modification of work by “KUERT Datenrettung”/Flickr)

As the demand for lanthanide materials has increased faster than supply, prices have also increased. In 2008, dysprosium cost \$110/kg; by 2014, the price had increased to \$470/kg. Increasing the supply of lanthanoid elements is one of the most significant challenges facing the industries that rely on the optical and magnetic properties of these materials.

The transition elements have many properties in common with other metals. They are almost all hard, high-melting solids that conduct heat and electricity well. They readily form alloys and lose electrons to form stable cations. In addition, transition metals form a wide variety of stable coordination compounds, in which the central metal atom or ion acts as a Lewis acid and accepts one or more pairs of electrons. Many different molecules and ions can donate lone pairs to the metal center, serving as Lewis bases. In this chapter, we shall focus primarily on the chemical behavior of the elements of the first transition series.

### 2.1.1: Properties of the Transition Elements

Transition metals demonstrate a wide range of chemical behaviors. As can be seen from their reduction potentials (Table P1), some transition metals are strong reducing agents, whereas others have very low reactivity. For example, the lanthanides all form stable  $3+$  aqueous cations. The driving force for such oxidations is similar to that of alkaline earth metals such as Be or Mg, forming  $\text{Be}^{2+}$  and  $\text{Mg}^{2+}$ . On the other hand, materials like platinum and gold have much higher reduction potentials. Their ability to resist oxidation makes them useful materials for constructing circuits and jewelry.

Ions of the lighter  $d$ -block elements, such as  $\text{Cr}^{3+}$ ,  $\text{Fe}^{3+}$ , and  $\text{Co}^{2+}$ , form colorful hydrated ions that are stable in water. However, ions in the period just below these ( $\text{Mo}^{3+}$ ,  $\text{Ru}^{3+}$ , and  $\text{Ir}^{2+}$ ) are unstable and react readily with oxygen from the air. The majority of simple, water-stable ions formed by the heavier  $d$ -block elements are oxyanions such as  $\text{MoO}_4^{2-}$  and  $\text{ReO}_4^-$ .

Ruthenium, osmium, rhodium, iridium, palladium, and platinum are the platinum metals. With difficulty, they form simple cations that are stable in water, and, unlike the earlier elements in the second and third transition series, they do not form stable oxyanions.

Both the  $d$ - and  $f$ -block elements react with nonmetals to form binary compounds; heating is often required. These elements react with halogens to form a variety of halides ranging in oxidation state from  $1+$  to  $6+$ . On heating, oxygen reacts with all of the transition elements except palladium, platinum, silver, and gold. The oxides of these latter metals can be formed using other reactants, but they decompose upon heating. The  $f$ -block elements, the elements of group 3, and the elements of the first transition series except copper react with aqueous solutions of acids, forming hydrogen gas and solutions of the corresponding salts.

Transition metals can form compounds with a wide range of oxidation states. Some of the observed oxidation states of the elements of the first transition series are shown in Figure 2.1.4. As we move from left to right across the first transition series, we see that the number of common oxidation states increases at first to a maximum towards the middle of the table, then decreases. The values in the table are typical values; there are other known values, and it is possible to synthesize new additions. For example, in 2014, researchers were successful in synthesizing a new oxidation state of iridium ( $9+$ ).

21	22	23	24	25	26	27	28	29	30
Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
		2+	2+	2+	2+	2+	2+	1+	
3+	3+	3+	3+	3+	3+	3+	3+	2+	2+
	4+	4+	4+	4+				3+	
		5+							
			6+	6+	6+				
				7+					

Figure 2.1.4: Transition metals of the first transition series can form compounds with varying oxidation states.

For the elements scandium through manganese (the first half of the first transition series), the highest oxidation state corresponds to the loss of all of the electrons in both the  $s$  and  $d$  orbitals of their valence shells. The titanium(IV) ion, for example, is formed when the titanium atom loses its two  $3d$  and two  $4s$  electrons. These highest oxidation states are the most stable forms of scandium, titanium, and vanadium. However, it is not possible to continue to remove all of the valence electrons from metals as we continue through the series. Iron is known to form oxidation states from  $2+$  to  $6+$ , with iron(II) and iron(III) being the most common. Most of the elements of the first transition series form ions with a charge of  $2+$  or  $3+$  that are stable in water, although those of the early members of the series can be readily oxidized by air.

The elements of the second and third transition series generally are more stable in higher oxidation states than are the elements of the first series. In general, the atomic radius increases down a group, which leads to the ions of the second and third series being larger than are those in the first series. Removing electrons from orbitals that are located farther from the nucleus is easier than removing electrons close to the nucleus. For example, molybdenum and tungsten, members of group 6, are limited mostly to an oxidation state of  $6+$  in aqueous solution. Chromium, the lightest member of the group, forms stable  $\text{Cr}^{3+}$  ions in water and, in the

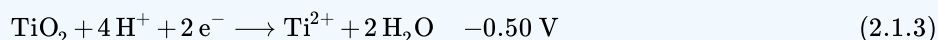
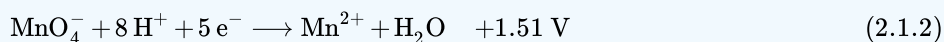
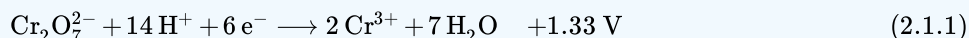
absence of air, less stable  $\text{Cr}^{2+}$  ions. The sulfide with the highest oxidation state for chromium is  $\text{Cr}_2\text{S}_3$ , which contains the  $\text{Cr}^{3+}$  ion. Molybdenum and tungsten form sulfides in which the metals exhibit oxidation states of 4+ and 6+.

### ✓ Example 2.1.2: Activity of the Transition Metals

Which is the strongest oxidizing agent in acidic solution: dichromate ion, which contains chromium(VI), permanganate ion, which contains manganese(VII), or titanium dioxide, which contains titanium(IV)?

#### Solution

First, we need to look up the reduction half reactions (Table P1) for each oxide in the specified oxidation state:

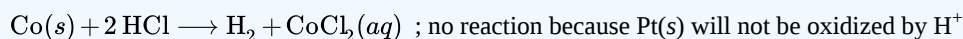


A larger reduction potential means that it is easier to reduce the reactant. Permanganate, with the largest reduction potential, is the strongest oxidizer under these conditions. Dichromate is next, followed by titanium dioxide as the weakest oxidizing agent (the hardest to reduce) of this set.

### ? Exercise 2.1.2

Predict what reaction (if any) will occur between  $\text{HCl}$  and  $\text{Co(s)}$ , and between  $\text{HBr}$  and  $\text{Pt(s)}$ . You will need to use the standard reduction potentials from (Table P1).

#### Answer



## 2.1.2: Preparation of the Transition Elements

Ancient civilizations knew about iron, copper, silver, and gold. The time periods in human history known as the Bronze Age and Iron Age mark the advancements in which societies learned to isolate certain metals and use them to make tools and goods. Naturally occurring ores of copper, silver, and gold can contain high concentrations of these metals in elemental form (Figure 2.1.5). Iron, on the other hand, occurs on earth almost exclusively in oxidized forms, such as rust ( $\text{Fe}_2\text{O}_3$ ). The earliest known iron implements were made from iron meteorites. Surviving iron artifacts dating from approximately 4000 to 2500 BC are rare, but all known examples contain specific alloys of iron and nickel that occur only in extraterrestrial objects, not on earth. It took thousands of years of technological advances before civilizations developed iron smelting, the ability to extract a pure element from its naturally occurring ores and for iron tools to become common.

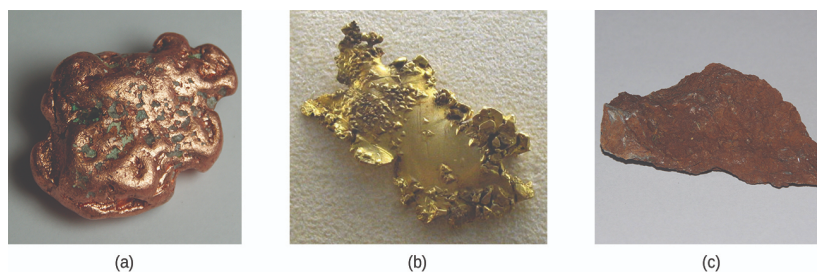


Figure 2.1.5: Transition metals occur in nature in various forms. Examples include (a) a nugget of copper, (b) a deposit of gold, and (c) an ore containing oxidized iron. (credit a: modification of work by <http://images-of-elements.com/copper-2.jpg>; credit c: modification of work by <http://images-of-elements.com/iron-ore.jpg>)

Generally, the transition elements are extracted from minerals found in a variety of ores. However, the ease of their recovery varies widely, depending on the concentration of the element in the ore, the identity of the other elements present, and the difficulty of reducing the element to the free metal.

In general, it is not difficult to reduce ions of the *d*-block elements to the free element. Carbon is a sufficiently strong reducing agent in most cases. However, like the ions of the more active main group metals, ions of the *f*-block elements must be isolated by

electrolysis or by reduction with an active metal such as calcium.

### 2.1.3: High Temperature Superconductors

A superconductor is a substance that conducts electricity with no resistance. This lack of resistance means that there is no energy loss during the transmission of electricity. This would lead to a significant reduction in the cost of electricity.

Most currently used, commercial superconducting materials, such as NbTi and Nb<sub>3</sub>Sn, do not become superconducting until they are cooled below 23 K (−250 °C). This requires the use of liquid helium, which has a boiling temperature of 4 K and is expensive and difficult to handle. The cost of liquid helium has deterred the widespread application of superconductors.

One of the most exciting scientific discoveries of the 1980s was the characterization of compounds that exhibit superconductivity at temperatures above 90 K. (Compared to liquid helium, 90 K is a high temperature.) Typical among the high-temperature superconducting materials are oxides containing yttrium (or one of several rare earth elements), barium, and copper in a 1:2:3 ratio. The formula of the ionic yttrium compound is YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>.

The new materials become superconducting at temperatures close to 90 K (Figure 2.1.10), temperatures that can be reached by cooling with liquid nitrogen (boiling temperature of 77 K). Not only are liquid nitrogen-cooled materials easier to handle, but the cooling costs are also about 1000 times lower than for liquid helium.

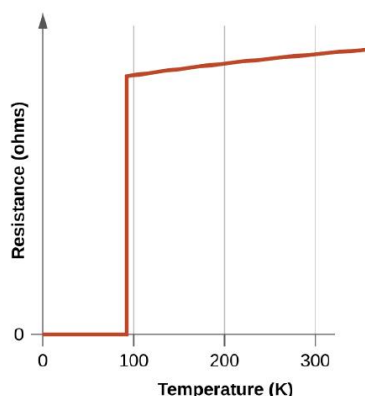
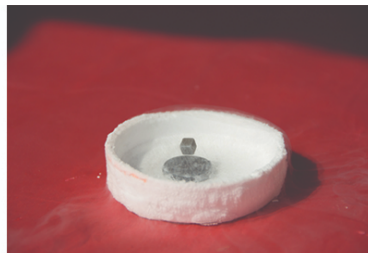


Figure 2.1.10: The resistance of the high-temperature superconductor YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> varies with temperature. Note how the resistance falls to zero below 92 K, when the substance becomes superconducting.

Although the brittle, fragile nature of these materials presently hampers their commercial applications, they have tremendous potential that researchers are hard at work improving their processes to help realize. Superconducting transmission lines would carry current for hundreds of miles with no loss of power due to resistance in the wires. This could allow generating stations to be located in areas remote from population centers and near the natural resources necessary for power production. The first project demonstrating the viability of high-temperature superconductor power transmission was established in New York in 2008.



(a)



(b)

Figure 2.1.11: (a) This magnetic levitation train (or maglev) uses superconductor technology to move along its tracks. (b) A magnet can be levitated using a dish like this as a superconductor. (credit a: modification of work by Alex Needham; credit b: modification of work by Kevin Jarrett)

Researchers are also working on using this technology to develop other applications, such as smaller and more powerful microchips. In addition, high-temperature superconductors can be used to generate magnetic fields for applications such as medical devices, magnetic levitation trains, and containment fields for nuclear fusion reactors (Figure 2.1.11).





Video 2.1.1: Watch how a high-temperature superconductor levitates around a magnetic racetrack in the video.

## Summary

The transition metals are elements with partially filled  $d$  orbitals, located in the  $d$ -block of the periodic table. The reactivity of the transition elements varies widely from very active metals such as scandium and iron to almost inert elements, such as the platinum metals.

Transition metals exhibit chemical behavior typical of metals. Most transition metals form a variety of stable oxidation states, allowing them to demonstrate a wide range of chemical reactivity.

## Glossary

### actinide series

(also, actinoid series) actinium and the elements in the second row or the  $f$ -block, atomic numbers 89–103

### $d$ -block element

one of the elements in groups 3–11 with valence electrons in  $d$  orbitals

### $f$ -block element

(also, inner transition element) one of the elements with atomic numbers 58–71 or 90–103 that have valence electrons in  $f$  orbitals; they are frequently shown offset below the periodic table

### first transition series

transition elements in the fourth period of the periodic table (first row of the  $d$ -block), atomic numbers 21–29

### fourth transition series

transition elements in the seventh period of the periodic table (fourth row of the  $d$ -block), atomic numbers 89 and 104–111

### lanthanide series

(also, lanthanoid series) lanthanum and the elements in the first row or the  $f$ -block, atomic numbers 57–71

### platinum metals

group of six transition metals consisting of ruthenium, osmium, rhodium, iridium, palladium, and platinum that tend to occur in the same minerals and demonstrate similar chemical properties

### rare earth element

collection of 17 elements including the lanthanides, scandium, and yttrium that often occur together and have similar chemical properties, making separation difficult

### second transition series

transition elements in the fifth period of the periodic table (second row of the  $d$ -block), atomic numbers 39–47

**superconductor**

material that conducts electricity with no resistance

**third transition series**

transition elements in the sixth period of the periodic table (third row of the *d*-block), atomic numbers 57 and 72–79

## Contributors and Attributions

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