Predicting Inorganic Reaction Products:
A Critical Thinking Exercise in General Chemistry

David G. DeWit

Department of Chemistry, Augustana College, Rock Island, IL 61201; *davedewit@augustana.edu.*

Most educators hope that students, by the end of a course or sequence of courses, are able to apply diverse ideas, principles, facts, and skills to solve important problems. A popular strategy at the college level is to introduce a capstone exercise near the end of a series of courses that requires the application of a wide range of knowledge and skills. Successful completion of such an exercise is regarded as evidence that students' cognitive thinking levels have increased during the course of study *(1, 2)*.

In a typical general chemistry sequence, students are exposed to a large number of principles, facts, and skills that they often perceive as disconnected and irrelevant. Learning chemistry, especially for first-year students, often consists of memorizing facts, definitions, or sets of steps for solving isolated problems of limited scope (cognitive level 1 in Bloom's *Taxonomy;* ref *1*).

As a college chemistry teacher, I have been discouraged by students' inability, even at the end of a yearlong general chemistry course, to make reasonable predictions about the reactivity of elements and of simple inorganic compounds. At first this surprised me, because the process merely requires an application of principles covered earlier that most students seemed to understand. Clearly the obstacle for students stems from the necessity to understand the principles well enough to be able to apply several of them at one time. I began to believe that the ability to tie together and apply diverse principles to make valid judgments about chemical reactions would constitute a valuable critical thinking exercise for general chemistry students and would help them advance to higher cognitive levels of thinking *(1, 2)*.

A few years ago I began inserting a one-week (three class periods) reactions module near the end of my three-term general chemistry sequence designed to connect the process of predicting the products of a variety of simple inorganic reactions with the principles previously learned in the general chemistry course. This module, introduced in the third term of the sequence, occurs after covering the usual core general chemistry topics (stoichiometry, electronic structure, bonding, states of matter, solutions, equilibrium, kinetics, thermodynamics, electrochemistry) but is done before embarking on the more descriptive topics (chemistry of the representative elements, coordination chemistry of the transition metals, organic chemistry) that comprise the final chapters of many general chemistry texts.

The goal of the module is to empower first-year chemistry students to understand, explain, and predict (rather than merely memorize) what happens when chemical substances are mixed. The list of possible examples for the reaction categories is nearly endless so that every problem set, quiz, or test on this material could be different. The fact that reaction products must be "figured out" causes considerable anxiety among the students for whom learning has been limited to memorizing. The degree of cognitive growth my students experience in response to the module is widely varying, but I believe their overall progress is significant.

The Reactions Module

The module is based on a handout that presents examples of inorganic reactions in three broad categories (oxidation–reduction, acid–base, and reactions of water) along with rationales for reaction products that draw upon familiar principles. The reaction categories are discussed below, listing at least one example in each case and some of the key principles that must be applied to deduce reasonable reaction products. In my classes I usually present several examples in each category, first giving only the reactants and then prompting the students through the critical thinking steps necessary to arrive at reasonable products and an acceptable balanced chemical equation.

The process of balancing equations is the least important part of this exercise and should be done last, after formulas for the products are determined. Students whose first concern is balancing an equation often choose product formulas based solely on what it takes to balance the equation most easily.

The initial concern should be to analyze the nature of the reactant substances carefully enough to place the reaction in the proper category. I expect students to predict the course of reactions based on a straightforward application of periodic properties. More than one product is often possible, but I am usually satisfied if students are able to write a single reaction that makes sense. I do not expect students, at this point, to be aware of specific reaction conditions that favor one product over another nor of conditions that result in exceptions to the simple predictions based on periodic properties. Particular examples of how reaction conditions affect reactivity, sometimes selectively and sometimes unexpectedly, are discussed during my later unit on descriptive chemistry.

Oxidation–Reduction Reactions

Main-group elements generally lose or gain electrons in reactions to achieve valence electron configurations ns^0, ns^2, or ns^2np^6. Students should know stable oxidation states of several common transition metals in compounds.

Understanding the fundamental distinction between metals and nonmetals is essential. In this exercise students are expected to predict relative metallic and nonmetallic character based solely on position in the periodic table unless other information (e.g., standard reduction potentials) is given.

Element + Element

$$4\,Sb \;+\; 5\,O_2 \;\longrightarrow\; 2\,Sb_2O_5 \;(\text{or } Sb_2O_3)$$
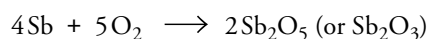
Reactivity: The more metallic element gets oxidized and the more nonmetallic element gets reduced.

Principles: Significance of electron transfer in oxidation–reduction reactions; the chemical difference between metals and nonmetals; relative metallic and nonmetallic character assessed from the periodic table; expected stable oxidation states for families of main-group elements based on valence electron configurations; combining elements in positive and negative oxidation states to form neutral binary compounds.

Of course this straightforward approach to predicting products in this category can fail, as in the reaction of N_2 with O_2. NO_x chemistry and other special cases are worthy topics introduced at a later point in my course.

Element + Compound (Element = Metal)

$$3\,Mg + 2\,CoF_3 \longrightarrow 3\,MgF_2 + 2\,Co \text{ (or } CoF_2\text{)}$$

$$Mg + KCl \longrightarrow \text{ no reaction}$$
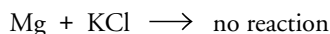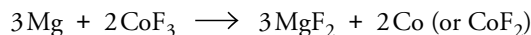
Reactivity: The metal gets oxidized and an element in the compound gets reduced.

Principles: Chemical behavior of metallic elements; predicting relative metal activities from the periodic table; using standard reduction potentials when necessary; the nature of oxidation–reduction reactions; assigning oxidation states in compounds; predicting allowed oxidation states of reducible main-group elements in compounds; balancing charges as well as atoms in a reaction.

Element + Compound (Element = Nonmetal)

$$2\,F_2 + 2\,H_2O \longrightarrow 4\,HF + O_2$$

$$Br_2 + 2\,NaCl \longrightarrow \text{ no reaction}$$

$$O_2 + 2\,SO_3^{2-} \longrightarrow 2\,SO_4^{2-}$$

$$O_2 + SO_3 \longrightarrow \text{ no new product}$$
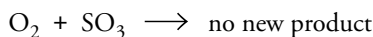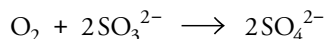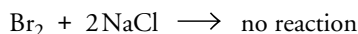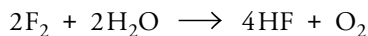
Reactivity: The nonmetal gets reduced and an element in the compound gets oxidized.

Principles: Chemical behavior of nonmetal elements; assessing relative nonmetallic character from the periodic table; using standard reduction potentials when necessary; predicting allowed higher oxidation states of oxidizable main-group elements in compounds; balancing charges as well as atoms in a reaction.
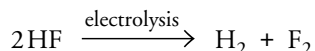
Decomposition

Thermal Decomposition:

$$2\,HgO(s) \xrightarrow{\Delta} 2\,Hg(l) + O_2(g)$$
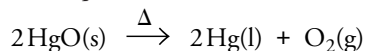
Reactivity: If $\Delta S > 0$, a metallic element in the compound gets reduced and the nonmetal element gets oxidized at temperatures high enough to make $\Delta G\, (= \Delta H - T\Delta S) < 0$.

Principles: Second law of thermodynamics and the effect of temperature on entropy-driven reactions.
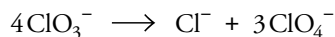
Electrolysis:

$$2\,HF \xrightarrow{\text{electrolysis}} H_2 + F_2$$

Reactivity: An applied potential reduces the positive element in the compound at the cathode and oxidizes the negative element in the compound at the anode.

Principles: Electrochemical cells; anodes and cathodes; effect of applied potential in electrolytic cells.

Disproportionation:

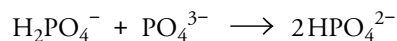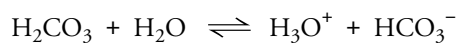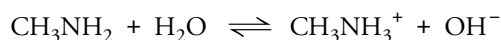$$4\,ClO_3^- \longrightarrow Cl^- + 3\,ClO_4^-$$

Reactivity: An element in a compound both oxidizes and reduces, achieving stable oxidation states above and below the original oxidation state.

Principles: Assessing relative stabilities of various oxidation states of a given element; use of standard reduction potentials to predict spontaneity.

In a testing situation, I often identify a reaction as disproportionation and give the formula of one of the products.

Acid–Base

Brønsted Definition

$$CH_3NH_2 + H_2O \rightleftharpoons CH_3NH_3^+ + OH^-$$

$$H_2CO_3 + H_2O \rightleftharpoons H_3O^+ + HCO_3^-$$

$$H_2PO_4^- + PO_4^{3-} \longrightarrow 2\,HPO_4^{2-}$$

Principles: Acid–base equilibrium; use of tabulated acid and base dissociation constants to predict direction of H^+ transfer; amphoteric behavior; conjugate acids and bases; balancing charges as well as atoms in chemical equations.

Lewis Definition

$$Fe^{+3} + 6\,H_2O \longrightarrow [Fe(H_2O)_6]^{3+}$$

$$BF_3 + F^- \longrightarrow BF_4^-$$
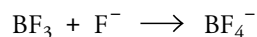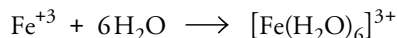
Reactivity: Species with a lone pair of valence electrons share the electron pair with a species with at least one empty valence orbital to form a coordinate bond.

Principles: Valence orbitals and valence electron configurations; valence bond theory; coordination number.

Lux–Flood Definition

$$SnO_3^{2-} + SbO_2^+ \longrightarrow SnO_2 + SbO_3^-$$

$$SnO_2 + SO_2 \longrightarrow SnO^{2+} + SO_3^{2-}$$
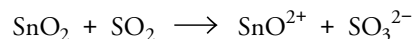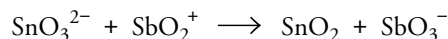
Reactivity: O^{2-}, a good ionic bonder, maximizes its bond energy by seeking out smaller atoms with higher oxidation states, a simple application of Coulomb's law. Even though Lux–Flood behavior *(3)* is not normally introduced in general chemistry textbooks, many general chemistry students have seen reactions driven by this principle, especially reactions of oxides with water and some metathesis reactions.

Principles: Assessing oxophilicity based on oxidation state and size; using oxophilicity to predict the direction of O^{2-} transfer.

Students should not be surprised by apparent exceptions to the predictions of the oxophilicity series. For example H^+, because of its small size, is normally more oxophilic than typical 2+ cations. Similarly, large centers (e.g., Pb^{4+}) can be less oxophilic than oxidation states might predict.

Reactions of H$_2$O

Although some of the reactions in this section duplicate those in the above categories, the multifaceted chemistry of water is worth special mention. Water is oxidizable (e.g., by F$_2$), reducible (e.g., by Na), or decomposable by electrolysis. Water is amphoteric in all three acid–base definitions mentioned above. Its polarity and high dielectric constant confers a special ability to dissociate dissolved electrolytes.
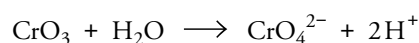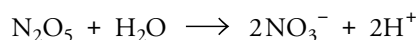
Lux–Flood Acid or Base

As an Acid:

$$CaO + H_2O \longrightarrow Ca^{2+} + 2OH^-$$

$$Na_2O + H_2O \longrightarrow 2Na^+ + 2OH^-$$
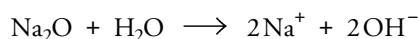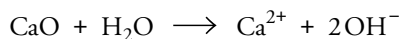
Principle: H$^+$ is more oxophilic are than normal 2+ and 1+ ions.

Students may need a little extra guidance here because transfer of O^{2-} to H$_2$O might be thought to yield "H$_2$O$_2^{2-}$" as a product. Writing two separate OH$^-$ ions is necessary because a stable Lewis structure is not possible for H$_2$O$_2^{2-}$.

As a Base:

$$SO_2 + H_2O \longrightarrow SO_3^{2-} + 2H^+ (H_2SO_3)$$

$$N_2O_5 + H_2O \longrightarrow 2NO_3^- + 2H^+$$

$$CrO_3 + H_2O \longrightarrow CrO_4^{2-} + 2H^+$$

Principle: Elements in oxidation states 3+ and higher are generally more oxophilic than H$^+$.

A rule that many students have learned is that "metal oxides are basic and nonmetal oxides are acidic". Note that this principle does not always work. Predictions based on the notion of oxophilicity are safer.

Hydrolysis of Halides of Elements in High (≥ 3+) Oxidation States

$$TiCl_4 + H_2O \longrightarrow TiOCl_2 + 2HCl \text{ (or TiO}_2\text{)}$$

Reactivity: O^{2-} displaces two halides from the compound in a metathesis reaction.

Principles: Oxophilicity; driving forces for metathesis reactions.

Brønsted Acid or Base

$$H_2O + NH_2^- \longrightarrow OH^- + NH_3$$

$$H_2O + HNO_3 \longrightarrow H_3O^+ + NO_3^-$$
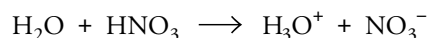
Principles: acid and base strength; amphoteric substances.

Dissolving and Dissociating Electrolytes

$$Fe_2(SO_4)_3(s) \xrightleftharpoons{H_2O} Fe_2(SO_4)_3(aq) \text{ (saturated)}$$

$$Fe_2(SO_4)_3(aq) \longrightarrow 2Fe^{3+}(aq) + 3SO_4^{2-}(aq)$$

$$HC_7H_5O_2(s) \xrightarrow{H_2O} HC_7H_5O_2(aq) \text{ (unsaturated)}$$

$$HC_7H_5O_2(aq) \rightleftharpoons H^+(aq) + C_7H_5O_2^-(aq)$$
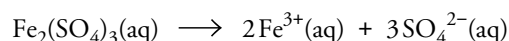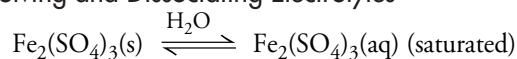
Table 1. Results of the Diagnostic Quiz

Class	Correct Responses[a,c]	Incorrect Responses[a]	Mean Score[b,c]
General Chemistry[d]			
Before	8.3 (±3.2)	13.8 (±3.5)	−5.5
After	19.1 (±5.4)	6.8 (±4.7)	12.3
Introductory Inorganic[e]			
Before	8.8 (±2.6)	14.9 (±4.1)	−6.1
After:	20.1 (±4.3)	7.0 (±4.3)	13.1

[a]Standard deviations in parentheses. [b]Score = number of correct responses – number of incorrect responses. [c]Maximum possible is 32. [d]37 students. [e]24 students.

Reactivity: Solutes dissolve either completely or partially, depending how the amount of solute added compares to its solubility. Once dissolved, strong electrolytes are assumed to dissociate completely into ions, and dissolved weak electrolytes ionize only partially.

Principles: Strong electrolytes versus weak electrolytes; solubility equilibrium versus equilibrium dissociation of dissolved solutes; formulas (including charges) for common cations and anions; recognizing ionic compounds.

Assessment

The diagnostic quiz shown in Figure 1 was given in two of my courses during the 2004–2005 academic year: third-term general chemistry course and introductory inorganic chemistry course. Each of these courses follows the first two terms of our three-term general chemistry sequence. Most of our prehealth students opt to take the third term of general chemistry, while chemistry majors and minors are urged to take the inorganic course. In each course, the quiz was given twice under supervised, controlled conditions: first, before the reactions module but after completing the first 20 chapters of our textbook *(4)*; and second, one week after completing the module but before beginning the descriptive chemistry component of the courses.

The results are summarized in Table 1. Scores (maximum possible is 32) were computed by subtracting the number of incorrect responses from the number of correct responses. Note that in both cases the post-module (after) average score was significantly higher than the pre-module (before) score. General chemistry and inorganic students improved by an average 17.8 and 19.2 points, respectively. Although these average post-module scores are still significantly lower than the maximum possible score it is clear, for example, from the improvement in final exam scores since using the module, that the students' command and appreciation of simple chemical reactivity is markedly greater than it would have been without the module.

Summary

Although predicting products for the simple reactions in this article may seem trivial to chemistry educators, I find that the exercise is far from trivial for first-year chemistry students, even though most of them demonstrate an adequate understanding of the individual principles when they encounter the

For each reaction, mark (x) each possible set of products that is consistent with predicted periodic properties. In some cases, **more than one correct answer is possible** as a result of varying temperatures, pressures, solvents, and combining ratios. Compounds are expressed with empirical formulas only. Correct answers need not result in balanced equations. Score = number of choices marked correctly – number of choices marked incorrectly.

$In + Cl_2 \longrightarrow$
___ $InCl_4$
___ In_3Cl
[x] $InCl_3$
___ In_2Cl
[x] $InCl$
___ $InCl_5$
___ In_2Cl_3
___ no reaction

$Cl_2 + I_2 \longrightarrow$
[x] ICl
___ $I^- + Cl^-$
___ ClI_7
[x] ICl_5
[x] ICl_3
___ Cl_2I_2
[x] ICl_7
___ ClI_5
___ ClI_3
___ no reaction

$P + O_2 \longrightarrow$
___ PO
___ PO_4
___ PO_2
[x] P_2O_3
[x] P_2O_5
___ P_2O
___ PO_4^{3-}
___ no reaction

$Ca + PCl_5 \longrightarrow$
___ $CaCl + PCl_4$
___ $CaP + Cl_5$
___ $Ca_3P_2 + Cl_2$
[x] $CaCl_2 + PCl_3$
___ $CaPCl_5$
[x] $CaCl_2 + P$
___ $CaCl_5 + P$
___ no reaction

$Ca + K_2O \longrightarrow$
___ $CaO + K$
___ $Ca^{2+} + K_2O$
___ $CaKO$
___ $Ca_2O + K$
___ $CaO + K^+$
___ $CaK_2 + O$
[x] no reaction

$O_2 + SO_3^{2-} \longrightarrow$
___ $O_3^{2-} + SO_2$
[x] SO_4^{2-}
___ $O^{2-} + SO_3^{2-}$
___ $O + SO_4^{2-}$
___ SO_5^{2-}
___ SO_5
___ $O^{2-} + SO_4$
___ no reaction

$O_2 + CaF_2 \longrightarrow$
___ $F_2 + CaO$
___ $F_2 + CaO_2$
___ $O^{2-} + F^- + Ca^{2+}$
___ $F^- + CaO$
___ $O_2F_2 + Ca$
[x] no reaction

$F_2 + AlCl_3 \longrightarrow$
___ $Al + Cl_3F_2$
___ $AlCl_3F_2$
___ $F_2^- + AlCl_3^+$
[x] $AlF_3 + Cl_2$
___ no reaction

$F_2 + PF_5 \longrightarrow$
___ $PF_6 + F$
___ $PF_4 + F_3$
___ PF_7
___ $PF_3 + F_4$
___ $PF_6^- + F^-$
[x] no reaction

thermal decomposition of $AuCl_3$:
___ $Au^{3+} + Cl^-$
___ $Au^{3+} + Cl_2$
___ $Au + Cl^-$
___ $AuCl^{2+} + Cl_2$
[x] $AuCl + Cl_2$
___ $Au + Cl_3$
[x] $Au + Cl_2$
___ no reaction

electrolysis of $FeBr_3$:
___ $Fe^{+3} + Br_3^-$
___ $FeBr^{2+} + Br_2$
___ $Fe + Br_3$
[x] $Fe^{2+} + Br_2$
[x] $Fe + Br_2$
___ $Fe^{3+} + Br^-$
___ no reaction

disproportionation of ClO_2^-:
___ $Cl^- + ClO_2^-$
___ $ClO_3^- + ClO_4^-$
[x] $Cl^- + ClO_3^-$
[x] $ClO^- + ClO_3^-$
___ $ClO_2^- + ClO_4^-$
[x] $ClO^- + ClO_4^-$
[x] $Cl^- + ClO_4^-$
___ $Cl^- + ClO^-$
___ no reaction

N_2H_4 (Bronsted base)
+ HN_3 (Bronsted acid) $\longrightarrow$
___ $N_3 + N_2H_5$
___ $H_2N_3^+ + N_2H_3^-$
___ $H_2N_3^- + N_2H_3$
[x] $N_3^- + N_2H_5^+$
___ no reaction

$Sn^{4+} + 6Cl^- \longrightarrow$
___ $SnCl_6$
___ $SnCl_4 + Cl_2$
[x] $SnCl_6^{2-}$
___ $SnCl_6^{4+}$
___ $6SnCl$
___ no reaction

$BiO_2^+ + PbO_2 \longrightarrow$
___ $BiO^{2+} + PbO_3^-$
___ $BiO_3^+ + PbO$
[x] $BiO_3^- + PbO^{2+}$
___ $BiO^+ + PbO_3$
___ $BiO^{3+} + PbO_3^{2-}$
___ $BiO_3 + PbO^{5+}$
___ no reaction

$BiO_2^+ + SO_3 \longrightarrow$
___ $BiO^+ + SO_4$
___ $BiO_3^+ + SO_2$
___ $BiO_3^+ + SO_3^{2+}$
[x] $BiO^{3+} + SO_4^{2-}$
___ $BiO + SO_4$
___ $BiO_3 + SO_2$
___ no reaction

$H_2O + CrO_3 \longrightarrow$
___ $CrO_2^{2+} + OH^-$
[x] $CrO_4^{2-} + H^+$
___ $CrO_4 + H_2$
___ $CrO_4^{2-} + H_2$
___ $CrO_2 + H_2O_2$
___ $CrO_2^{2+} + H_2O_2^{2-}$
___ no reaction

$H_2O + K_2O \longrightarrow$
___ $K_2O_2^{2-} + H_2^+$
[x] $K^+ + OH^-$
___ $KO^- + H^+$
___ $K_2^+ + OH^-$
___ $K_2^+ + H_2O_2^{2-}$
___ $K_2O_2^{2-} + H^+$
___ no reaction

$H_2O + SiCl_4 \longrightarrow$
___ $H_2SiCl_2 + O$
[x] $SiO_2 + HCl$
___ $SiO + HCl$
[x] $SiOCl_2 + HCl$
___ $SiH_4 + OCl_2$
___ $SiCl_2 + H_2OCl_2$
___ no reaction

$CaCl_2(aq) \longrightarrow$
___ $Ca^{2+} + Cl^+$
___ $Ca^+ + Cl^-$
___ $Ca^{2+} + Cl_2^-$
___ $Ca^+ + Cl_2^-$
___ $Ca + Cl_2$
[x] $Ca^{2+} + Cl^-$
___ $CaCl + Cl$
___ no reaction

Figure 1. Quiz used to assess the effectiveness of the module.

principles earlier in the course. I have become convinced that this capstone exercise is well worth the time and effort because it allows students to understand that seemingly unrelated topics in general chemistry are actually relevant to what real chemistry is about, that is, making sense of what happens when substances interact. As such, I have also found the exercise to be a helpful prelude to discussions of descriptive topics. Many of the reactions encountered in a survey of elements and their compounds are specific examples of the reaction types mentioned in this article, and the module has helped my students remember and appreciate details about the chemical behavior of specific substances introduced later in the course.

Quite aside from helping to deepen chemical understanding, I regard the module described in this article as the kind of exercise much needed by all first-year college students:

practice in thinking critically and in making connections within a discipline.

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