Research Article

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A new classification scheme for teaching reaction types in general chemistry

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Abstract:
General chemistry is a freshman-level class required for most science majors and pre-professional undergraduates. A variety of concepts are introduced in this course; among them, chemical reactions are fundamental, but remain a central topic. The author compared 10 textbooks widely used for college-level general chemistry courses. They all cover the three major classes of chemical reactions: precipitation reactions, acid-base reactions, and oxidation-reduction (redox) reactions. However, significant differences in the way these textbooks present the material may cause confusion and misunderstanding for students, including when they move to upper-level courses. The author suggests a modified reaction classification scheme for general chemistry courses, which will provide students a more complete and nuanced understanding of chemical reactions.

Keywords: chemical reactions, chemistry textbooks, freshman-level course, general chemistry, reaction classifications

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General chemistry is a freshman-level class required for most science majors and pre-professional undergraduates. A variety of concepts are introduced in this course, including stoichiometry of formulas and equations, chemical reactions, electronic structure and periodic properties of elements, chemical bonding and molecular geometry, gases, liquids and solids, solutions and colloids, kinetics, equilibrium, thermodynamics, electrochemistry, transition metals and coordination chemistry, and nuclear chemistry. Among these topics, chemical reactions are fundamental, but remain a central component of chemistry.

There are millions of known compounds and millions of possible chemical reactions. To better understand how substances interact with one other, chemists group chemical reactions into classes based on their reaction patterns. There are different ways to classify chemical reactions; the most commonly used classification system is introduced to students via general chemistry textbooks.

The author investigated 10 textbooks widely used for general chemistry teaching (Table 1). All of them introduce the three major classes of chemical reactions: precipitation reactions, acid-base reactions, and oxidation-reduction (redox) reactions. However, significant differences exist between the treatments of the topic. Some textbooks do not indicate that precipitation and acid-base reactions are subclasses of double-displacement/exchange/metathesis reactions; others do not point out the subtypes of redox reactions when elements are involved in the reaction, such as combination redox, decomposition redox, single-displacement/replacement, and combustion reactions. In addition, some textbooks do not clearly indicate that there are combination and decomposition reactions not belonging to the redox reaction subgroup; others do not provide examples of redox reactions not involving elements.

Table 1: Comparison of the classification of chemical reactions from 10 general chemistry textbooks.

Reaction classifications	Referenced textbook
– Chapter 3 introduces (1) combination reactions, (2) decomposition reactions, and (3) combustion reactions – Chapter 4 introduces (4) precipitation reactions (this textbook indicates that reactions in which cations and anions exchange partners are called exchange or metathesis reactions), (5) acid-base reactions, and (6) oxidation-reduction reactions (this textbook indicates that reactions between a metal and either an acid or a metal salt are called displacement reactions)	Brown et al. (2018), Chemistry: The central science 14th ed.
– Chapter 4 introduces (1) precipitation reactions, (2) acid-base reactions, and (3) oxidation-reduction reactions (this textbook introduces combustion as an application of oxidation-reduction reactions)	McMurry, Fay, and Robinson (2016), Chemistry 7th ed.

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– Chapter 8 introduces (1) combination reactions, (2) decomposition reactions, (3) single-displacement reactions, and (4) double-displacement reactions including (a) neutralization reactions between an acid and a base, (b) reactions between a metal oxide and an acid, (c) precipitation reactions, and (d) double-displacement reactions accompanied by the formation of a gas – Chapter 17 introduces (5) oxidation-reduction reactions	Hein and Arena (2014), Foundations of college chemistry 14th ed.
– Chapter 3 introduces (1) combination reactions, and (2) combustion reactions – Chapter 4 introduces (3) acid-base reactions, (4) precipitation reactions, and (5) oxidation-reduction reactions	Gilbert, Kirss, Foster, and Davies (2015), Chemistry: The science in context 4th ed.
– Chapter 4 introduces (1) precipitation reactions (this textbook indicates that reactions in which ions exchange partners are called double-displacement or metathesis reactions), (2) acid-base reactions, and (3) oxidation-reduction reactions including (a) combination redox reactions, (b) decomposition redox reactions, (c) single-displacement reactions, and (d) combustion reactions	Silberberg (2013), Principles of general chemistry 3rd ed.
– Chapter 4 introduces (1) precipitation reactions (this textbook indicates that precipitation reactions are examples of metathesis/double-displacement reactions), (2) acid-base reactions, and (3) oxidation-reduction reactions including (a) combination reactions, (b) decomposition reactions, (c) combustion reactions, (d) displacement reactions, and (e) disproportionation reactions	Chang and Overby (2019), Chemistry 13th ed.
– Chapter 4 introduces (1) precipitation reactions (this textbook indicates that reactions involving the exchange of parts between two reactants are called exchange or metathesis reactions), (2) acid-base reactions, and (3) oxidation-reduction reactions including (a) combination reactions, (b) decomposition reactions, (c) single-displacement reactions, and (d) combustion reactions	Ebbing and Gammon (2017), General chemistry 11th ed.
– Chapter 4 introduces (1) precipitation reactions (this textbook indicates that precipitation reactions also can be called double displacement reactions), (2) acid-base reactions, and (3) oxidation-reduction reactions (this textbook indicates that combustion reactions involve oxidation and reduction)	Zumdahl, Zumdahl, and DeCoste (2018), Chemistry 10th ed.
– Chapter 4 introduces (1) combustion reactions, (2) decomposition reactions, and (3) combination reactions – Chapter 5 introduces (4) precipitation reactions, (5) acid-base reactions, and (6) oxidation-reduction reactions (this textbook points out disproportionation reactions as examples of oxidation-reduction reactions)	Petrucci, Herring, Madura, and Bissonnette (2017), General chemistry: Principles and modern applications 11th ed.
– Chapter 4 introduces (1) precipitation reactions (this textbook indicates that reactions involving the exchange of ions between ionic compounds in aqueous solution are sometimes called double-displacement/replacement or metathesis reactions), (2) acid-base reactions, and (3) oxidation-reduction reactions (this textbook indicates that combustion reactions and single-displacement/replacement reactions are subclasses of oxidation-reduction reactions)	Flowers, Theopold, Langley, and Robinson (2018), Chemistry, OpenStax 2018 Rice University

The inconsistency of reaction classifications in general chemistry textbooks may cause confusion: First, students may not know what double-displacement/metathesis reactions are if they are only taught the three major classes of chemical reactions (i.e. precipitation reactions, acid-base reactions, and oxidation-reduction reactions); second, although detailed examples are given from one or more subclasses of redox reactions when teaching the redox reaction category, students may not realize that certain combination and decomposition reactions, along with single-displacement and combustion reactions, are subtypes of redox reactions if the names of these subclasses are not made clear; third, if combination and decomposition reactions are only introduced under the redox category, students may not realize that there are also combination and decomposition reactions not belonging to the redox category; and fourth, if only the redox subclasses involving elements are introduced, students may not realize that there are also redox reactions not involving elements. The author has not found any publication that addresses the differences between reaction classification systems in chemistry textbooks, nor on clarifying the confusion that arises from current classification systems. In order to address these problems, the author suggests a modified classification scheme for teaching about reaction types in general chemistry.

The author groups the major chemical reactions into four categories: (1) double-displacement reactions, (2) oxidation-reduction (redox) reactions, (3) combination reactions that are not redox reactions, and (4) decomposition reactions that are not redox reactions. Precipitation and acid-base reactions are classified as separate subtypes of double-displacement reactions. The redox category is first divided into two subgroups: redox reactions not involving elements, and redox reactions involving elements. The combination redox, decomposition redox, single-displacement, and combustion reactions then become four subclasses of "redox reactions involving elements," along with the fifth subclass called "other redox reactions involving elements as reactants and/or products."

Assigning the two major classes of chemical reactions – precipitation and acid-base reactions – both to group (1) allows students to observe their similarity (i.e. both are double-displacement reactions). Dividing group (2) – redox reactions – into two subgroups helps students realize that redox reactions may or may not involve elements; as long as electron transfer occurs (i.e. a change in oxidation number for atoms in a reaction), it is a redox reaction. Including five subclasses in the "redox reactions involving elements" subgroup provides students a complete view of the possible ways to arrange elements in both reactants and products. Furthermore, presenting groups (3) and (4) allows students to understand that not all combination and decomposition reactions are redox reactions.

Reaction examples and notations are associated with each reaction category, as shown below. By using this classification method, undergraduate students should gain a more complete and nuanced view of chemical reactions while taking general chemistry, which will build a stronger foundation for learning advanced chemical reactions from the domains of organic, inorganic, and biochemistry.

Modified reaction classifications

(1) Double-displacement/replacement reactions – also called exchange or metathesis reactions; parts of two ionic compounds exchange places, making two new compounds.

(1-1) ***Precipitation reactions*** – soluble ionic compounds exchange ions and form an insoluble product/precipitate (Note: Teachers should introduce the solubility rules for common ionic compounds in water).

$$\text{e.g. } BaCl_2(aq) + K_2SO_4(aq) \rightarrow BaSO_4(s) + 2KCl(aq)$$

$$2AgNO_3(aq) + CaCl_2(aq) \rightarrow 2AgCl(s) + Ca(NO_3)_2(aq)$$

$$3NaOH(aq) + Fe(NO_3)_3(aq) \rightarrow Fe(OH)_3(s) + 3NaNO_3(aq)$$

$$Pb(NO_3)_2(aq) + 2KI(aq) \rightarrow PbI_2(s) + 2KNO_3(aq)$$

(1-2) ***Acid-base reactions*** – an acid transfers proton(s) to a base (Note: Teachers should introduce common strong/weak acids and bases).

e.g. $H_2SO_4(aq) + 2KOH(aq) \rightarrow K_2SO_4(aq) + 2H_2O(l)$ (Note: This reaction is also called a neutralization reaction: an acid reacts with a base to form a salt and water.)

$$2HCl(aq) + CaO(s) \rightarrow CaCl_2(aq) + H_2O(l)$$

$$NH_4Cl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l) + NH_3(aq)$$

$$2HCl(aq) + Na_2S(aq) \rightarrow 2NaCl(aq) + H_2S(g)$$

(Note: Not all acid-base reactions produce salt and water.)

(2) Oxidation-reduction (redox) reactions – electron(s) move from one species to the other; the reactant that loses electron(s) is oxidized and is called the reducing agent; the reactant that gains electron(s) is reduced and is called the oxidizing agent (Note: Teachers should introduce the rules for assigning an oxidation number, and how to use oxidation numbers to identify oxidizing and reducing agents).

(2-1) ***Redox reactions not involving elements***

$$\text{e.g. } 2KMnO_4(aq) + 10FeSO_4(aq) + 8H_2SO_4(aq) \rightarrow K_2SO_4(aq) + 2MnSO_4(aq) + 5Fe_2(SO_4)_3(aq) + 8H_2O(l)$$

$$2KMnO_4(aq) + 3KIO_3(aq) + H_2O(l) \rightarrow 2MnO_2(s) + 3KIO_4(aq) + 2KOH(aq)$$

$$6FeSO_4(aq) + K_2Cr_2O_7(aq) + 7H_2SO_4(aq) \rightarrow Cr_2(SO_4)_3(aq) + 3Fe_2(SO_4)_3(aq) + K_2SO_4(aq) + 7H_2O(l)$$

$$2FeSO_4(aq) + 2Ce(SO_4)_2(aq) \rightarrow Fe_2(SO_4)_3(aq) + Ce_2(SO_4)_3(aq)$$

(2-2) ***Redox reactions involving elements***

(2-2-1) Combination redox reactions – two or more reactants (at least one of which is an element) combine to form a compound.

$$\text{e.g. } F_2(g) + H_2(g) \rightarrow 2HF(g)$$

$$2Al(s) + 3Br_2(l) \rightarrow 2AlBr_3(s)$$

$$2Mg(s) + O_2(g) \xrightarrow{\Delta} 2MgO(s) \text{ (Note: This is also a combustion reaction.)}$$

$$P_4(s) + 5O_2(g) \rightarrow P_4O_{10}(s) \text{ (Note: This is also a combustion reaction.)}$$

(2-2-2) Decomposition redox reactions – a compound decomposes to form two or more products, at least one of which is an element.

$$\text{e.g. } 2HgO(s) \xrightarrow{\Delta} 2Hg(l) + O_2(g)$$

$$2KClO_3(s) \xrightarrow{\Delta} 2KCl(s) + 3O_2(g)$$

$$2NH_4ClO_4(s) \xrightarrow{\Delta} N_2(g) + Cl_2(g) + 4H_2O(g) + 2O_2(g)$$

$2H_2O_2(aq) \xrightarrow{\Delta} 2H_2O(l) + O_2(g)$ (Note: This reaction is also called a disproportionation reaction: the reactant contains an element which can have at least three oxidation states, and the same reactant is both oxidized and reduced.)

(2-2-3) Single-displacement/replacement reactions – one reactant is an element, which displaces an ion or atom from another reactant, forming a new element and a new compound (Note: Teachers should introduce the activity series of the metals and the halogens).

$$\text{e.g. } Cu(s) + 2AgNO_3(aq) \rightarrow 2Ag(s) + Cu(NO_3)_2(aq)$$

$$Zn(s) + H_2SO_4(aq) \rightarrow ZnSO_4(aq) + H_2(g)$$

$$2Na(s) + 2H_2O(l) \rightarrow 2NaOH(aq) + H_2(g)$$

$$Cl_2(g) + 2KBr(aq) \rightarrow Br_2(l) + 2KCl(aq)$$

(2-2-4) Combustion reactions – a substance reacts with oxygen (Note: When organic molecules combust, the reaction produces CO_2 and H_2O; not all combustion reactions release CO_2 and H_2O).

$$\text{e.g. } CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

$$2CH_3OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 4H_2O(g)$$

$$C_6H_{12}O_6(s) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(g)$$

$$B_2H_6(g) + 3O_2(g) \rightarrow B_2O_3(s) + 3H_2O(g)$$

(2-2-5) Other redox reactions involving elements as reactants and/or products

$$\text{e.g. } PbO(s) + CO(g) \rightarrow Pb(s) + CO_2(g)$$

$$2N_2H_4(l) + 2NO_2(g) \rightarrow 3N_2(g) + 4H_2O(l)$$

$$16KNO_3(s) + S_8(s) + 24C(s) \rightarrow 8K_2S(s) + 8N_2(g) + 24CO_2(g)$$

$$KClO_4(s) + 2C(s) \rightarrow KCl(s) + 2CO_2(g)$$

(3) Combination reactions not belonging to redox reactions – two or more reactants, none of which is an element, combine to form a compound (Note: Combination reactions that belong to redox reactions are included in the redox reaction category).

$$\text{e.g. } CaO(s) + H_2O(l) \rightarrow Ca(OH)_2(aq)$$

$$P_2O_5(s) + 3H_2O(l) \rightarrow 2H_3PO_4(aq)$$

$$NH_3(g) + HCl(g) \rightarrow NH_4Cl(s)$$

$$MgO(s) + CO_2(g) \rightarrow MgCO_3(s)$$

(4) Decomposition reactions not belonging to redox reactions – a compound decomposes to form two or more products, none of which is an element (Note: Decomposition reactions that belong to redox reactions are included in the redox reaction category).

$$\text{e.g. } CaCO_3(s) \xrightarrow{\Delta} CaO(s) + CO_2(g)$$

$$2NaHCO_3(s) \xrightarrow{\Delta} Na_2CO_3(s) + H_2O(g) + CO_2(g)$$

$$2Fe(OH)_3(s) \xrightarrow{\Delta} Fe_2O_3(s) + 3H_2O(l)$$

$$H_2CO_3(aq) \rightarrow H_2O(l) + CO_2(g)$$

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References

Brown, T. L., LeMay, H. E. Jr., Bursten, B. E., Murphy, C. J., Woodward, P. M., Stoltzfus, M. W., & Lufaso, M. W. (2018). *Chemistry: The central science* (14th ed.). New York, NY: Pearson.
Chang, R., & Overby, J. (2019). *Chemistry* (13th ed.). New York, NY: McGraw-Hill.
Ebbing, D. D., & Gammon, S. D. (2017). *General chemistry* (11th ed.). Boston, MA: Cengage.
Flowers, P., Theopold, K., Langley, R., & Robinson, W. R. (2018). *Chemistry*. Houston, TX: OpenStax.
Gilbert, T. R., Kirss, R. V., Foster, N., & Davies, G. (2015). *Chemistry: The science in context* (4th ed.). New York, NY: W W. Norton.
Hein, M., & Arena, S. (2014). *Foundations of college chemistry* (14th ed.). Hoboken, N.J.: Wiley.
McMurry, J. E., Fay, R. C., & Robinson, J. K. (2016). *Chemistry* (7th ed.). New York, NY: Pearson.
Petrucci, R. H., Herring, F. G., Madura, J. D., & Bissonnette, C. (2017). *General chemistry: Principles and modern applications* (11th ed.). Toronto, ON: Pearson.
Silberberg, M. S. (2013). *Principles of general chemistry* (3rd ed.). New York, NY: McGraw-Hill.
Zumdahl, S. S., Zumdahl, S. A., & DeCoste, D. J. (2018). *Chemistry* (10th ed.). Boston, MA: Cengage.