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From Balancing Redox Reactions to Determining Change of Oxidation Numbers

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Redox reaction is a core concept in teaching and learning chemistry. This article explores a new method for balancing organic redox reactions that requires the balancing of both atoms and charges. The H^+, O, H_2O, and e^- are used as balanced vehicles in two half reactions. A non-oxidation number approach can be applied to both molecular and ionic equations. The article also provides standard operating procedures and examples. The number of transferred electrons is first determined by balancing a half redox reaction; consequently; the change of oxidation numbers can be calculated. The mathematical equation of $Te^- = n\,\Delta ON$ is established, and the change of oxidation numbers (ΔON) can be counted by the number of transferred electrons (Te^-) and the number of atoms with oxidation numbers change (n). By using this mathematical equation as a new approach, students can conveniently calculate the change of mean oxidation numbers for an assigned atom in a half redox reaction.

Redox reaction is a core concept in teaching and learning chemistry (Goodstein, 1970). The oxidation number method has been widely used for balancing redox reactions, and the determination of the oxidation number is a required step in the process (Herndon, 1997; Chang & Goldsby, 2013; Tro, 2014; Generalic & Vladislavic, 2018). However, the act of balancing organic redox reactions often poses problems for students (Lockwood, 1961; Jensen, 2009). In this article, we discuss a new method, the proton method, that can be applied to both molecular and ionic chemical equations. The method can be used for not only balancing redox equations but also determining the number of transferred electrons and the change of oxidation numbers.

Proton method: Procedures for balancing half reactions

This section shows how the proton method is used to balance both atoms and charges. H^+, O, H_2O, and e^- are used as vehicles in two half reactions.

Step 1. Balance atoms.
Step 1.1. Balance all other atoms except H and O.
Step 1.2. Balance hydrogen atoms with H^+.
Step 1.3. Balance oxygen atoms with O.
Step 1.4. Add two H^+ atoms for each O atom.
Step 1.5. Convert two H^+ and one O to one H_2O molecule.

Step 2. Balance charges.
Step 2.1. Count the number of charges on both sides.
Step 2.2. Add electrons to make charges on both sides equivalent.

Step 3. Convert H^+ to OH^- (optional step when working in a basic medium).
Step 3.1. Add one OH^- for each H^+.
Step 3.2. Convert one OH^- and one H^+ to one H_2O molecule.
Step 3.3. Simplify an overall equation.

Examples for balancing molecular half reactions

Example 1

Convert the equation $CH_3CH_2OH \rightarrow CH_3COOH$ to $C_2H_6O \rightarrow C_2H_4O_2$.

Step 1. Balance atoms.

$C_2H_6O \rightarrow C_2H_4O_2$
$C_2H_6O + O \rightarrow C_2H_4O_2 + 2H^+$
$C_2H_6O + O + 2H^+ \rightarrow C_2H_4O_2 + 2H^+ + 2H^+$
$C_2H_6O + H_2O \rightarrow C_2H_4O_2 + 4H^+$

Step 2. Balance charges.

$C_2H_6O + H_2O \rightarrow C_2H_4O_2 + 4H^+$
(0) (+4)
$C_2H_6O + H_2O \rightarrow C_2H_4O_2 + 4H^+ + 4e^-$

Example 2

Convert the equation $CH_3CH_2CH_3 \rightarrow CO_2$ to $C_3H_8 \rightarrow CO_2$.

Step 1. Balance atoms.

$C_3H_8 \rightarrow CO_2$
$C_3H_8 \rightarrow 3CO_2$

$C_3H_8 + 6O \rightarrow 3CO_2 + 8H^+$
$C_3H_8 + 6O + 12H^+ \rightarrow 3CO_2 + 8H^+ + 12H^+$
$C_3H_8 + 6H_2O \rightarrow 3CO_2 + 20H^+$

Step 2. Balance charges.
$C_3H_8 + 6H_2O \rightarrow 3CO_2 + 20H^+$
(0) (+20)
$C_3H_8 + 6H_2O \rightarrow 3CO_2 + 20H^+ + 20e^-$

Examples for balancing ionic half reactions

Example 3

Given an ionic equation $Cr_2O_7^{2-} \rightarrow Cr^{3+}$ (in acidic medium):

Step 1. Balance atoms.
$Cr_2O_7^{2-} \rightarrow Cr^{3+}$
$Cr_2O_7^{2-} \rightarrow 2Cr^{3+}$
$Cr_2O_7^{2-} \rightarrow 2Cr^{3+} + 7O$
$Cr_2O_7^{2-} + 14H^+ \rightarrow 2Cr^{3+} + 7O + 14H^+$
$Cr_2O_7^{2-} + 14H^+ \rightarrow 2Cr^{3+} + 7H_2O$

Step 2. Balance charges.
$Cr_2O_7^{2-} + 14H^+ \rightarrow 2Cr^{3+} + 7H_2O$
(+12) (+6)
$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O$

Example 4

Given an ionic equation $MnO_4^- \rightarrow MnO_2$ (in basic medium):

Step 1. Balance atoms.
$MnO_4^- \rightarrow MnO_2$
$MnO_4^- \rightarrow MnO_2 + 2O$
$MnO_4^- + 4H^+ \rightarrow MnO_2 + 2O + 4H^+$
$MnO_4^- + 4H^+ \rightarrow MnO_2 + 2H_2O$

Step 2. Balance charges.
$MnO_4^- + 4H^+ \rightarrow MnO_2 + 2H_2O$
(+3) (0)
$MnO_4^- + 4H^+ + 3e^- \rightarrow MnO_2 + 2H_2O$

Step 3. Convert H^+ to OH^- (in basic medium).
$MnO_4^- + 4H^+ + 3e^- \rightarrow MnO_2 + 2H_2O$
$MnO_4^- + 4H^+ + 3e^- + 4OH^- \rightarrow MnO_2 + 2H_2O + 4OH^-$
$MnO_4^- + 4H_2O + 3e^- \rightarrow MnO_2 + 2H_2O + 4OH^-$
$MnO_4^- + 2H_2O + 3e^- \rightarrow MnO_2 + 4OH^-$

Determination of Te^- in a balanced half redox reaction

First, one needs to balance atoms and charges, then the number of transferred electrons can be determined accordingly. In Example 1, the reaction of $C_2H_6O + H_2O \rightarrow C_2H_4O_2 + 4H^+ + 4e^-$, a loss of four electrons identifies an oxidation reaction. In Example 3, the reaction of $Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O$, a gain of six electrons identifies a reduction reaction. An oxidation reaction can be represented by $Te^- > 0$ (positive value), and a reduction reaction can be represented by $Te^- < 0$ (negative value). These half-reaction examples are quantified and defined in Table 1.

TABLE 1

Quantifying and defining half redox reactions.

Example of half redox reaction	Te^-	Electrons	Type
$C_2H_6O + H_2O \rightarrow C_2H_4O_2 + 4H^+ + 4e^-$	+4	loss	oxidation
$C_3H_8 + 6H_2O \rightarrow 3CO_2 + 20H^+ + 20e^-$	+20	loss	oxidation
$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O$	−6	gain	reduction
$MnO_4^- + 2H_2O + 3e^- \rightarrow MnO_2 + 4OH^-$	−3	gain	reduction

Relationship among Te^-, n, and ΔON in balanced half redox reactions

Based on Examples 1 through 4, the values of Te^-, n, and ΔON are shown in Table 2. In Table 2, Te^-, n, and ΔON denote the number of transferred electrons, the number of atoms with oxidation number change, and the change of mean oxidation numbers, respectively. ΔON can be counted by the difference between the oxidation number of an atom on the product side (ON_f) and the oxidation number of an atom on the reactant side (ON_i), and it is demonstrated by $\Delta ON = ON_f - ON_i$. An oxidation reaction can be represented by $\Delta ON > 0$ (positive value), and a reduction reaction can be represented by $\Delta ON < 0$ (negative value).

TABLE 2

Quantifying Te^-, *n*, and ΔON in half redox reactions.

Example of half redox reaction	Atom with oxidation numbers change	Te^-	*n*	ΔON
$C_2H_6O + H_2O \rightarrow C_2H_4O_2 + 4H^+ + 4e^-$	C	+4	2	+2
$C_3H_8 + 6H_2O \rightarrow 3CO_2 + 20H^+ + 20e^-$	C	+20	3	$+\frac{20}{3}$
$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O$	Cr	−6	2	−3
$MnO_4^- + 2H_2O + 3e^- \rightarrow MnO_2 + 4OH^-$	Mn	−3	1	−3

In a balanced half reaction, the relationship among Te^-, n, and ΔON can be deducted, and the mathematical equation is shown as follows:

$$Te^- = n\,\Delta ON$$

Proton method: Procedures for balancing overall redox reactions

An overall number of transferred electrons is counted by the least common multiple (LCM) of two half redox reactions. The procedures for balancing an overall reaction are as follows:

Step 1. Divide into two half reactions.
Step 2. Balance all atoms in two half reactions.
Step 3. Balance charges of two half reactions by adding electrons.
Step 4. Make electrons of two half reactions equivalent.
Step 5. Combine and simplify two half reactions.
Step 6. Convert H^+ to OH^- (optional step when working in basic medium).

Examples for balancing overall redox reactions

Example 5

Convert the ionic chemical equation $CH_3CH_2OH + Cr_2O_7^{2-} \rightarrow CH_3COOH + Cr^{3+}$ (in acidic medium) to $C_2H_6O + Cr_2O_7^{2-} \rightarrow C_2H_4O_2 + Cr^{3+}$.

Step 1. Divide into two half reactions:

$C_2H_6O \rightarrow C_2H_4O_2$
$Cr_2O_7^{2-} \rightarrow Cr^{3+}$

Step 2. Balance all atoms in two half reactions.

$C_2H_6O \rightarrow C_2H_4O_2$
$C_2H_6O + O \rightarrow C_2H_4O_2 + 2H^+$
$C_2H_6O + O + 2H^+ \rightarrow C_2H_4O_2 + 2H^+ + 2H^+$
$C_2H_6O + H_2O \rightarrow C_2H_4O_2 + 4H^+$

$Cr_2O_7^{2-} \rightarrow 2Cr^{3+}$
$Cr_2O_7^{2-} \rightarrow 2Cr^{3+} + 7O$
$Cr_2O_7^{2-} + 14H^+ \rightarrow 2Cr^{3+} + 7O + 14H^+$
$Cr_2O_7^{2-} + 14H^+ \rightarrow 2Cr^{3+} + 7H_2O$

Step 3. Balance charges of two half reactions by adding electrons.

$C_2H_6O + H_2O \rightarrow C_2H_4O_2 + 4H^+ + 4e^-$
$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O$

Step 4. Make electrons of two half reactions equivalent (LCM = 12).

$(C_2H_6O + H_2O \rightarrow C_2H_4O_2 + 4H^+ + 4e^-) \times 3$
$(Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O) \times 2$

Step 5. Combine and simplify two half reactions.

$3C_2H_6O + 3H_2O + 2Cr_2O_7^{2-} + 28H^+ + 12e^- \rightarrow 3C_2H_4O_2 + 12H^+ + 4Cr^{3+} + 14H_2O + 12e^-$
$3C_2H_6O + 2Cr_2O_7^{2-} + 16H^+ \rightarrow 3C_2H_4O_2 + 4Cr^{3+} + 11H_2O$

Example 6

Convert molecular chemical equation $CH_3CH_2CH_3 + O_2 \rightarrow CO_2 + H_2O$ to $C_3H_8 + O_2 \rightarrow CO_2 + H_2O$.

Step 1. Divide into two half reactions.

$C_3H_8 \rightarrow CO_2$
$O_2 \rightarrow H_2O$

Step 2. Balance all atoms in two half reactions.

$C_3H_8 \rightarrow CO_2$
$C_3H_8 \rightarrow 3CO_2$
$C_3H_8 + 6O + 12H^+ \rightarrow 3CO_2 + 8H^+ + 12H^+$
$C_3H_8 + 6H_2O \rightarrow 3CO_2 + 20H^+$

$O_2 \rightarrow H_2O$
$O_2 \rightarrow 2H_2O$
$O_2 + 4H^+ \rightarrow 2H_2O$

Step 3. Balance charges of two half reactions by adding electrons.

$C_3H_8 + 6H_2O \rightarrow 3CO_2 + 20H^+ + 20e^-$
$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Step 4. Make electrons of the two half reactions equivalent (LCM = 20).

$(C_3H_8 + 6H_2O \rightarrow 3CO_2 + 20H^+ + 20e^-) \times 1$
$(O_2 + 4H^+ + 4e^- \rightarrow 2H_2O) \times 5$

Step 5. Combine and simplify two half reactions.

$C_3H_8 + 6H_2O + 5O_2 + 20H^+ + 20e^- \rightarrow 3CO_2 + 20H^+ + 10H_2O + 20e^-$
$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$

Example 7

Convert ionic chemical equation $CH_3CHO + Cu^{2+} \rightarrow CH_3COO^- + Cu_2O$ (in basic medium) to $C_2H_4O + Cu^{2+} \rightarrow C_2H_3O_2^- + Cu_2O$.

Step 1. Divide into two half reactions.

$C_2H_4O \rightarrow C_2H_3O_2^-$
$Cu^{2+} \rightarrow Cu_2O$

Step 2. Balance all atoms in two half reactions.

$C_2H_4O \rightarrow C_2H_3O_2^-$
$C_2H_4O + O \rightarrow C_2H_3O_2^- + H^+$
$C_2H_4O + O + 2H^+ \rightarrow C_2H_3O_2^- + H^+ + 2H^+$
$C_2H_4O + H_2O \rightarrow C_2H_3O_2^- + 3H^+$

$Cu^{2+} \rightarrow Cu_2O$
$2Cu^{2+} + O \rightarrow Cu_2O$
$2Cu^{2+} + O + 2H^+ \rightarrow Cu_2O + 2H^+$
$2Cu^{2+} + H_2O \rightarrow Cu_2O + 2H^+$

Step 3. Add electrons to balance charges of half reactions.

$C_2H_4O + H_2O \rightarrow C_2H_3O_2^- + 3H^+ + 2e^-$
$2Cu^{2+} + H_2O + 2e^- \rightarrow Cu_2O + 2H^+$

Step 4. Make electrons of two half reactions equivalent (LCM = 2).

$(C_2H_4O + H_2O \rightarrow C_2H_3O_2^- + 3H^+ + 2e^-) \times 1$
$(2Cu^{2+} + H_2O + 2e^- \rightarrow Cu_2O + 2H^+) \times 1$

Step 5. Combine and simplify into two half reactions.

$C_2H_4O + H_2O + 2Cu^{2+} + H_2O + 2e^- \rightarrow C_2H_3O_2^- + 3H^+ + Cu_2O + 2H^+ + 2e^-$
$C_2H_4O + 2Cu^{2+} + 2H_2O \rightarrow C_2H_3O_2^- + Cu_2O + 5H^+$

Step 6. Convert H^+ to OH^-.

$C_2H_4O + 2Cu^{2+} + 2H_2O \rightarrow C_2H_3O_2^- + Cu_2O + 5H^+$
$C_2H_4O + 2Cu^{2+} + 2H_2O + 5OH^- \rightarrow C_2H_3O_2^- + Cu_2O + 5H^+ + 5OH^-$
$C_2H_4O + 2Cu^{2+} + 2H_2O + 5OH^- \rightarrow C_2H_3O_2^- + Cu_2O + 5H_2O$
$C_2H_4O + 2Cu^{2+} + 5OH^- \rightarrow C_2H_3O_2^- + Cu_2O + 3H_2O$

Calculation of ΔON in balanced half redox reactions

By using the oxidation method, the oxidation numbers of atoms are first assigned, then the change of oxidation numbers and the number of transferred electrons are counted, and finally the given equation is balanced. The proton method works in a reverse direction. By balancing an equation, the number of transferred electrons can be determined first, then the change of oxidation numbers can be calculated. Here are two half reactions from Example 7 that demonstrate calculations:

Example 7a

Given the balanced half redox reaction: Reduction
$2Cu^{2+} + H_2O + 2e^- \rightarrow Cu_2O + 2H^+$

$$n_{Cu} = 2;\ Te^- = -2$$

$$\Delta ON = \frac{Te^-}{n}$$

$$\Delta ON_{Cu} = \frac{-2}{2} = -1$$

In $2Cu^{2+} + H_2O + 2e^- \rightarrow Cu_2O + 2H^+$, there are two copper atoms gaining two electrons in the half reduction reaction. The change of mean copper oxidation numbers (ΔON_{Cu}) from Cu^{2+} (ON_i) to Cu_2O (ON_f) equals –1.

Example 7b

Given the balanced half redox reaction: Oxidation
$C_2H_4O + H_2O \rightarrow C_2H_3O_2^- + 3H^+ + 2e^-$

$$n_C = 2;\ Te^- = +2$$

$$\Delta ON = \frac{Te^-}{n}$$

$$\Delta ON_C = \frac{+2}{2} = +1$$

In the balanced half equation of $C_2H_4O + H_2O \rightarrow C_2H_3O_2^- + 3H^+ + 2e^-$, two carbon atoms carry the oxidation numbers change and lose two electrons. The calculated change of mean carbon oxidation numbers (ΔONc) equals +1.

Example 8

Determine the change of mean carbon oxidation numbers (ΔONc) for a redox couple of $C_6H_5CH_3$ and C_6H_5COOH.

Solution

Step 1. Balance atoms.

$C_6H_5CH_3 \rightarrow C_6H_5COOH$
$C_7H_8 \rightarrow C_7H_6O_2$
$C_7H_8 + 2O \rightarrow C_7H_6O_2 + 2H^+$
$C_7H_8 + 2O + 4H^+ \rightarrow C_7H_6O_2 + 2H^+ + 4H^+$
$C_7H_8 + 2H_2O \rightarrow C_7H_6O_2 + 6H^+$

Step 2. Balance charges.

$C_7H_8 + 2H_2O \rightarrow C_7H_6O_2 + 6H^+$
$C_7H_8 + 2H_2O \rightarrow C_7H_6O_2 + 6H^+ + 6e^-$

Step 3. Determine change of mean carbon oxidation numbers.

$$C_7H_8 + 2H_2O \rightarrow C_7H_6O_2 + 6H^+ + 6e^-$$

$$n_C = 7;\ Te^- = +6$$

$$\Delta ON = \frac{Te^-}{n}$$

$$\Delta ONc = \frac{+6}{7} = +\frac{6}{7}$$

Example 9

Given a half redox reaction $C_6H_{12}O_6 \rightarrow CO_2$, determine the change of mean carbon oxidation numbers (ΔONc).

Solution

Step 1. Balance atoms.

$C_6H_{12}O_6 \rightarrow CO_2$
$C_6H_{12}O_6 \rightarrow 6CO_2$
$C_6H_{12}O_6 + 6O \rightarrow 6CO_2 + 12H^+$
$C_6H_{12}O_6 + 6O + 12H^+ \rightarrow 6CO_2 + 12H^+ + 12H^+$
$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+$

Step 2. Balance charges.

$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+$
$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^-$

Step 3. Determine change of mean carbon oxidation numbers.

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^-$$

$$n_C = 6; Te^- = +24$$

$$\Delta ON = \frac{Te^-}{n}$$

$$\Delta ONc = \frac{+24}{6} = +4$$

Conclusion

By using a non-oxidation number approach, the proton method can be used to balance atoms and charges in redox reactions for both molecular and ionic chemical equations. Regarding a balanced half redox equation, the mathematic equation of $Te^- = n\,\Delta ON$ is established. This offers a new approach to count the change of mean oxidation numbers for an assigned atom in a balanced half reaction.

References

Chang, R., & Goldsby, K. A. (2013). *Chemistry* (11th ed). McGraw-Hill International.

Generalic, E., & Vladislavic, N. (2018). Aggregate redox species method: An improved oxidation number change method for balancing redox equations. *Chemistry Journal*, *4*(3), 43–49. http://www.aiscience.org/journal/cj

Goodstein, M. P. (1970). Interpretation of oxidation-reduction. *Journal of Chemical Education*, *47*(6), 452–457. https://doi.org/10.1021/ed047p452

Herndon, W. C. (1997). On balancing chemical equations: Past and present. A critical review and annotated bibliography. *Journal of Chemical Education*, *74*(11), 1359–1362. https://doi.org/10.1021/ed074p1359

Jensen, W. B. (2009). Balancing redox equations. *Journal of Chemical Education*, *86*(6), 681–682. https://doi.org/10.1021/ed086p681

Karen, P., McArdle, P., & Takats, J. (2014). Toward a comprehensive definition of oxidation state (IUPAC Technical Report). *Pure and Applied Chemistry*, *86*(6), 1017–1081. https://doi.org/10.1515/ci-2014-0523

Karen, P., McArdle, P., & Takats, J. (2016). Comprehensive definition of oxidation state (IUPAC Recommendations 2016). *Pure and Applied Chemistry, 88*(8), 831–839. https://doi.org/10.1515/pac-2015-1204

Lockwood, K. L. (1961). Redox revisited. *Journal of Chemical Education*, *38*(6), 326–329. https://doi.org/10.1021/ed038p326

Tro, N. J. (2014). *Chemistry—A molecular approach* (3rd ed.).

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