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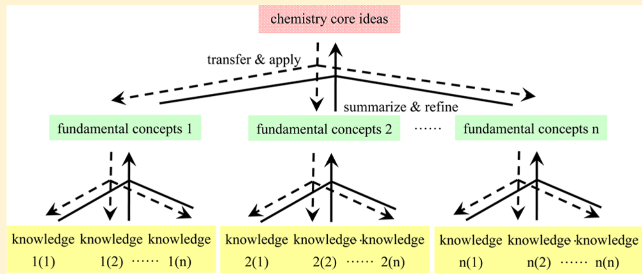
Representation and Analysis of Chemistry Core Ideas in Science Education Standards between China and the United States

Yanlan Wan and Hualin Bi*

College of Chemistry, Chemical Engineering and Materials Science, Shandong Normal University, Jinan, Shandong 250014, China

ABSTRACT: Chemistry core ideas play an important role in students' chemistry learning. On the basis of the representations of chemistry core ideas about *substances* and *processes* in the Chinese Chemistry Curriculum Standards (CCCS) and the U.S. Next Generation Science Standards (NGSS), we conduct a critical comparison of chemistry core ideas between these two documents in this paper. We also discuss the following reasons why there are differences in the representation of chemistry core ideas between them: different research perspectives on science education, different understandings of chemistry core ideas, and different understandings of the nature of teaching process. Our primary intent in this comparative analysis is to promote a deeper understanding of chemistry core ideas, provide advice and resources for chemistry curriculum research and chemistry teaching practice, and raise more attention on goals of science education and aims of chemistry.



KEYWORDS: *General Public, Curriculum, High School/Introductory Chemistry, Testing/Assessment, Learning Theories, Standards National/State*

■ INTRODUCTION

Chemistry core ideas as statements that summarize the most essential knowledge in chemistry[1] have attracted much attention in science education research in the past few decades. Researchers have systematically explicated the connotation of chemistry core ideas in theory[2,3] and organized chemistry curriculums around them in practice.[4,5] For example, the *Framework for K-12 Science Education*[6] and the associated *Next Generation Science Standards*[7] organize science content around three strands: disciplinary core ideas, crosscutting concepts, and science (and engineering) practices. A similar approach is found in the *Chinese Chemistry Curriculum Standards*,[8,9] which puts forward explicit requirements on chemistry core ideas in the *Curriculum Content* section.

The importance of chemistry core ideas for learning[10,11] and the authority of science education standards for teaching suggest that an analysis of chemistry core ideas in science education standards is of great significance. In 2014, Talanquer and Sevian reported a critical comparative analysis of chemistry core ideas between the *National Science Education Standards* (NSES) on the one hand, and the *Framework for K-12 Science Education* (FSE) and *Next Generation Science Standards* (NGSS) on the other.[12] How are chemistry core ideas presented in the *Chinese Chemistry Curriculum Standards* (CCCS)? What are the similarities and differences of chemistry core ideas in science education standards between China and the United States? These questions are both theoretically and practically important as science education is becoming more global as the result of economic globalization. Specifically, this comparative analysis and critical reflection can deepen our understanding of chemistry core ideas, raise more attention on the goals of science education, and provide specific guidance and advice to curriculum development, instruction, and assessment.

■ ANALYTICAL FRAMEWORK AND THE REPRESENTATION OF CHEMISTRY CORE IDEAS

In general, chemistry is depicted as a prototypical science that studies the properties, composition, and structure of substances; how substance structure and composition change; and the associated change in energy.[13] Meanwhile, chemistry is also a technoscience categorized and highlighted by various philosophers and historians recently.[14−16] Chemical scientists are interested in not only explaining and predicting properties of chemical substances, but also transforming them and creating new chemical entities with potential applications.[1] On the basis of this view on the nature of chemistry, we determined the analytical content and established an analytical framework for this study.

The nature of chemistry tells us that "substances" and "processes" are two central themes of chemistry. Therefore, chemistry core ideas about *substances* and *processes* included in the CCCS and the NGSS are chosen for analysis. In our analytical framework, disciplinary core ideas that define the fundamental scientific understanding of important concepts, principles, and methods are the central conceptual knowledge to the discipline. Students who learn chemistry concepts during different schooling periods gain different levels of conceptual understanding, which inevitably affects students' understanding and construction of chemistry core ideas.[17] Thus, conceptual dimensions and conceptual levels are used to analyze chemistry

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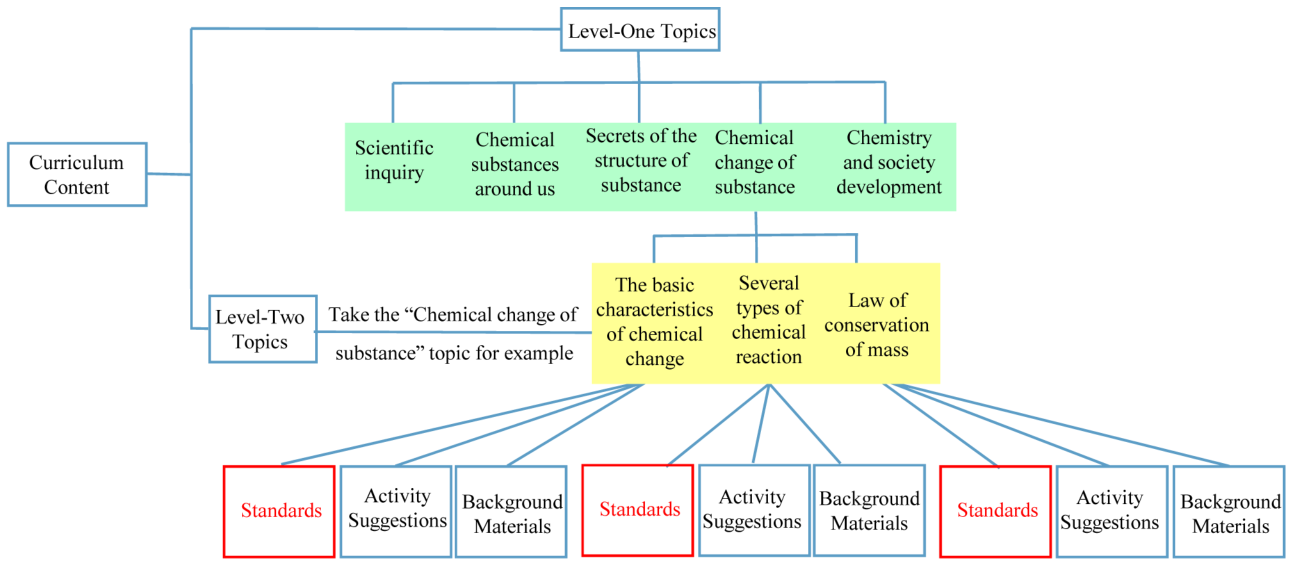

Figure 1. Basic structure of the CCCS[8,9] (Take the Junior High School Chemistry for Example).

core ideas in our study. We analyzed chemistry core ideas about *substances* from dimensions of state of matter, chemical composition, property, structure, and composition−structure−property relationship and analyzed chemistry core ideas about *processes* from dimensions of change, energy and time. Also, macro level, molecular level, and subatomic levels[18] were used to analyze the representation of chemistry core ideas. The selection of conceptual dimensions and conceptual levels is greatly influenced by the work of Claesgens et al.[19] on the conceptual framework, and Jensen[20] and Talanquer[21] on the structure of chemistry knowledge.

Chemistry Core Ideas in the CCCS

In China, chemistry is a separate science subject from biology and physics in school education and the CCCS is a separate standard accordingly. The CCCS is organized in terms of grade levels and topics. Specially, the CCCS is divided into three grade bands of junior high school chemistry, high school chemistry (compulsory), and high school chemistry (optional) corresponding to grades 7−9, grade 10, and grades 11−12, respectively. It should be noted that although the CCCS in grades 11−12 is optional, it does not mean that students in these grades have the right to give up chemistry learning completely. Instead, every student in these grades must take more than one level-one topic (module) to learn in order to meet the high school graduation requirements. This "compulsory in optional" form in grades 11−12 may be one of the most distinctive features in the CCCS.

There are four sections in the CCCS: *Preface*, *Curriculum Goals*, *Curriculum Content*, and *Implementation Suggestions*.[8,9] The *Curriculum Content* section includes level-one topics and level-two topics, and there are three small sections in each level-two topic: *standards*, *activity suggestions*, and *background materials*. The basic structure of the CCCS is shown in Figure 1. The CCCS does not present chemistry core ideas as an independent section. Instead, the *standards* section in the CCCS elaborates the chemistry core ideas that we expect nearly all students to understand. Therefore, chemistry core ideas about *substances* and *processes* we have chosen in the CCCS are from the *standards* section (marked in red in Figure 1). According to the analytical framework, we have organized chemistry core ideas in the CCCS into different groups (see Table 1). Limited to the space, Table 1 mainly lists the specific representation of chemistry core ideas and concepts related to the following discussion. Chemistry core ideas in the table are either copied in whole from the CCCS or paraphrased to fit the available space.

As shown in Table 1, the representation of chemistry core ideas about *substances* and *processes* in the CCCS is relatively rich and comprehensive on the whole. These chemistry core ideas are stated as behavioral goals and mainly include three types of chemistry concepts: (1) Theoretical Concepts (e.g., atomic structure, chemical bond, ionization, electrochemistry, chemical equilibrium); (2) Element and Compound Concepts (e.g., carbon, metals, acids and bases, organic compounds); and (3) Chemical Terminology and Calculation Concepts (e.g., chemical formula, calculation of the composition of matter and reaction heat). For conceptual levels, the representation of chemistry core ideas in the CCCS follows a learning progression from macroscopic level to molecular level to subatomic level as a whole. It suggests that the CCCS engages students in exploring the macroscopic properties and behaviors of different types of materials and substances to describe, explain, and predict the composition−structure−property relationships through analyzing their particulate and molecular models. This progression meets students' cognitive development principles and is helpful to promote students' chemistry learning.[18]

Chemistry Core Ideas in the NGSS

The system architecture of the NGSS[7] is illustrated in Figure 2. We have chosen the *Disciplinary Core Ideas* section under the *Performance Expectations* as the source for chemistry core ideas, and the majority of chemistry core ideas about *substances* and *processes* can be found under its *physical sciences* category (marked in red in Figure 2). In particular, we recognize that the *Performance Expectations* section in the NGSS provides a set of learning expectations that integrate science and engineering practices, core disciplinary ideas and crosscutting concepts, which is one of the most distinctive elements compared to prior science standards. However, the *Disciplinary Core Ideas* section, at least in terms of the NGSS, is meant to help clarify the *Performance Expectations* and describe where it comes from. Moreover, our primary intent in this paper is to elaborate and

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Table 1. Specific Chemistry Core Ideas and Concepts Included in the CCCS, Organized by Dimensions, Level of Representation, and Grade Band[a]

Dimensions	CCCS[8,9] Core Idea and Concept Articulations, by Grade Band and Level of Representation								
	Grades 7−9			Grade 10			Grades 11−12		
Substance Dimensions	Macro	Molecular	Subatomic	Macro	Molecular	Subatomic	Macro	Molecular	Subatomic
State of Matter	Knowing the three states of matter.	—	—	—	—	—	—	Illustrating the influence of intermolecular forces on the state of matter.	—
Chemical Composition	Knowing oxides from the perspective of elements.	Using chemical formulas to express the composition of matter. Using relative atomic/molecular mass to perform a simple calculation of the composition of matter.	—	Classifying matter according to its composition.	—	—	Knowing the composition of a hydrocarbon and its derivatives, synthetic polymers, etc.	Understanding general methods to measure the element content and relative molecular mass of organic compounds, and determining the corresponding molecular formula.	—
Property	Knowing main properties of commonly used metals, acids, and bases.	—	Identifying specific elements according to the atomic number of elements in the periodic table.	Classifying matter according to its properties.	—	—	Designing the separation and purification of matter according to its properties.	—	—
Structure	—	Knowing that molecules, atoms, and ions are particles of matter.	Knowing that atoms are made of a nucleus and electrons.	—	Understanding the bonding characteristics of carbon in organics.	Understanding the arrangement of extranuclear electrons.	—	Enumerating the basic packing model of metallic crystals.	Understanding the motion state of extranuclear electrons.
Composition−Structure−Property Relationship	Knowing that doping other elements in metals can change the performance of metallic materials.	Explaining common phenomena based on the view of particulate nature of matter.	—	—	—	Understanding the relationships between atomic structure and the properties of elements.	—	Using bond energy, bond length, and bond angle to explain certain properties of simple molecules.	—

	Grades 7−9			Grade 10			Grades 11−12		
Process Dimensions	Macro	Molecular	Subatomic	Macro	Molecular	Subatomic	Macro	Molecular	Subatomic
Change	Knowing the law of conservation of mass. Explaining quality relationships in the reaction. Illustrating the characteristics of the addition polymerization and polycondensation reactions. Understanding the oxygen cycle and carbon cycle in nature.	—	Understanding the role of extranuclear electron in chemical reactions.	Understanding the synthesis reaction of commonly used polymer materials through simple examples.	—	Knowing acids, bases, and salts can ionize in solution. Knowing the ionic reaction. Understanding the nature of redox reaction is electron transfer.	Explaining the reason why electrochemical corrosion can occur in metals. Describing the process of chemical equilibrium. Describing the precipitation and dissolution equilibrium. Knowing the nature of precipitation transformation.	Explaining the formation of ionic bonds.	Knowing that the transition of extranuclear electrons will occur under certain conditions.
Energy	Knowing that chemical change occurs with energy change.	—	—	Understanding that chemical energy and thermal energy can be converted to one another.	Knowing that the main reason why energy changes in reaction is the rupture and formation of chemical bonds.	—	Understanding the meaning of reaction heat and enthalpy change. Performing a simple calculation of reaction heat.	Knowing that lattice energy can be used to measure the strength of ionic bonds in ionic crystals.	—
Time	Knowing the important role of catalysts in chemical reactions.	—	—	Knowing that chemical reactions have different rates.	—	—	Knowing the meaning of activation energy and its influence on reaction rate.	—	—

[a]Note: Not every level of representation and grade band has an articulation for each substance or process dimension, as indicated by —.

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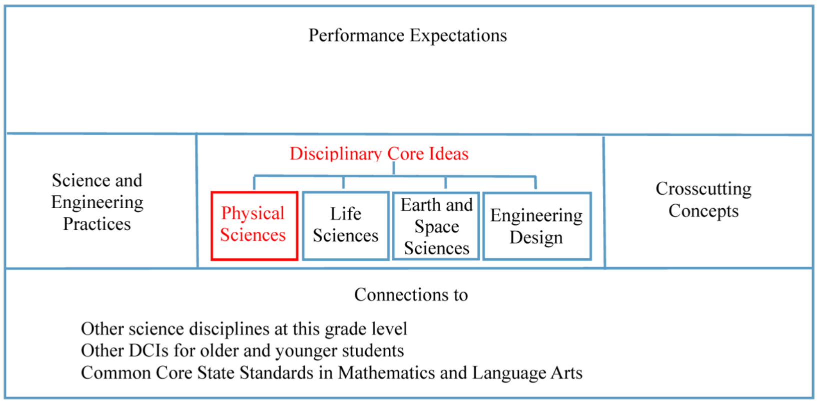

Figure 2. System architecture of the NGSS.[7]

compare chemistry core ideas, so the *Disciplinary Core Ideas* section is more comprehensive and coherent to some extent to be analyzed. Compared with the CCCS, chemistry core ideas included in middle school grades and high school grades in the NGSS correspond to grades 6−8 and grades 9−12. Table 2 shows the specific representation of chemistry core ideas and concepts included in the NGSS. Also, chemistry core ideas in Table 2 are taken from the NGSS either in whole or by paraphrasing to fit the available space.

From Table 2, we can see that chemistry core ideas about *substances* and *processes* in the *Disciplinary Core Ideas* section in the NGSS mainly include theoretical concepts (e.g., atoms, molecules, molecular collisions, atomic rearrangements, bond energies), with element and compound concepts and chemical terminology and calculation concepts barely mentioned. It seems that the NGSS emphasizes and approaches more focus on modeling and argumentation. For conceptual levels, the representation of chemistry core ideas pays more attention to molecular level and subatomic level.

THE COMPARATIVE ANALYSIS OF CHEMISTRY CORE IDEAS BETWEEN THE CCCS AND THE NGSS

The NGSS claims to be what all students should know and be able to do by the time they graduate from high school,[7] and the CCCS aims at promoting students' scientific literacy in order to prepare them to be informed citizens in the future.[8,9] It can be seen that the educational purposes pursued by the NGSS and the CCCS are consistent. In the following sections, we report a comparative analysis in terms of content representation, statement forms, conceptual levels, and learning progressions of chemistry core ideas. To highlight the differences of chemistry core ideas between the two documents, a summary table is presented at the end of these sections.

Content Representation of Chemistry Core Ideas

The analysis of Tables 1 and 2 reveals that there are some noticeable differences between the CCCS and the NGSS. For example, chemistry core ideas include theoretical concepts, element and compound concepts, and chemical terminology and calculation concepts in the CCCS, while the NGSS mainly includes theoretical concepts. In particular, concepts related to specific types of substances (e.g., oxides, metals, acids and bases, hydrocarbon and its derivatives, synthetic polymers) and chemical processes (e.g., redox reaction, addition polymerization and polycondensation reactions) are included in the CCCS but are barely mentioned in the *Disciplinary Core Ideas* section in the NGSS. Theoretical concepts are critical in understanding the nature of phenomena and explaining facts about properties and changes.[22] Therefore, it is not surprising that both the CCCS and the NGSS have paid enough attention to theoretical concepts. However, element and compound concepts as the foundation of chemistry learning provide the knowledge that a scientifically literate citizen should be expected to understand in the future.[12] Chemical terminology concepts are important means and tools for communication,[23] and chemical calculation concepts provide a fundamental prerequisite for quantitative research of chemistry.[24,25] These concepts are also beneficial to understand the chemistry core ideas and should be emphasized in curriculum standards. Further analysis shows that there are several chemistry ideas and concepts relating to fundamental chemistry activities in the CCCS, such as hydrocarbon and its derivative, addition polymerization and polycondensation reactions, synthetic polymers. This practical, socially relevant face of chemistry is barely visible in the NGSS.[12] As noted above, chemistry has also been characterized as a technoscience,[1] so more attention should be paid to the transformative and productive nature of chemistry.

While the *Disciplinary Core Ideas* section in the NGSS places relatively much emphasis on theoretical concepts, it should be specifically indicated that the *clarification statement* and *assessment boundary* in the *Performance Expectations* section in the NGSS contain a few specific chemical substances (e.g., ammonia, methanol, carbon dioxide, synthetic material) and processes (e.g., mixing zinc with hydrogen chloride, combustion reactions),[7] which, to some extent, compensates for some missing concepts discussed above.

Although the representation of chemistry core ideas seems relatively rich and strict in the CCCS, the NGSS when compared with the CCCS focuses more on some other chemistry concepts, especially concepts about *processes* (e.g., molecular collisions, rearrangement of atoms, attraction and repulsion between electronic charges, nuclear processes). These theoretical concepts emphasize molecular level and subatomic level and focus on exploring materials and substances from the perspective of their particulate nature, which implies that the NGSS places more emphasis on modeling, argumentation, logical thinking, and imagination in chemistry learning.

Statement Forms of Chemistry Core Ideas

One of the major differences in the CCCS when compared to the NGSS is the statement forms of chemistry core ideas. From Table 1, we can see that the CCCS adopts the form of *action verb and meaning* to express chemistry core ideas, in which the

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Table 2. Specific chemistry Core Ideas and Concepts Included in the NGSS, Organized by Dimensions, Level of Representation, and Grade Band[a]

Dimensions	NGSS[7] Disciplinary Core Ideas, by Grade Band and Level of Representation					
	Grades 6–8			Grades 9–12		
Substance Dimensions	Macro	Molecular	Subatomic	Macro	Molecular	Subatomic
State of Matter	—	States of matter differ in the relative spatial arrangement and movement of particles that make up the substance.	—	—	—	—
Chemical Composition	—	Substances are made from different types of atoms, which combine with one another in various ways.	—	—	—	—
Property	Each pure substance has characteristic physical and chemical properties that can be used to identify it.	—	—	—	—	Elements listed in order of atomic number exhibit periodic properties.
Structure	—	Matter is composed of atoms and molecules. Atoms form molecules that range in size from two to thousands of atoms. Gases and liquids are made of molecules or inert atoms that are moving about relative to each other.	—	—	A stable molecule has less energy than the same set of atoms separated.	Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons.
Composition–Structure–Property Relationship	—	—	—	—	—	Periodic properties reflect patterns of outer electron states. The structure and properties of matter are determined by electrical forces within and between atoms.

	Grades 6–8			Grades 9–12		
Process Dimensions	Macro	Molecular	Subatomic	Macro	Molecular	Subatomic
Change	Substances react chemically in characteristic ways. In a chemical process, new substances have different properties from those of the reactants.	The changes of state can be described and predicted using particulate models of matter. In a chemical process, the atoms that make up the original substances are regrouped into different molecules. The total number of each type of atom is conserved in a reaction, and thus the mass does not change.	—	—	Chemical processes are understood in terms of molecular collisions, rearrangement of atoms, and changes in the sum of all bond energies. The fact that atoms are conserved, together with knowledge of the chemical properties of the elements involved, can be used to describe and predict chemical reactions.	Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter.
Energy	Some chemical reactions release energy; others store energy.	Synthesis of food molecules in plants requires energy input. Cellular respiration in plants and animals involve chemical reactions with oxygen that release stored energy.	—	—	Energy transfer in chemical reactions results from changes in the sum of all bond energies matched by changes in kinetic energy.	Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.
Time	—	—	—	—	Reaction rates can be understood in terms of molecular collisions and atomic rearrangements. In many situations, balance between a reaction and the reverse reaction determines the numbers of all types of molecules present.	—

[a]Note: Not every level of representation and grade band has an articulation for each substance or process dimension, as indicated by —.

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Table 3. Comparison of Chemistry Core Ideas between the CCCS and the NGSS

Chemistry Core Ideas		CCCS[8,9]	NGSS[7]
Content representation	Theoretical concepts	Included	Included
	Element and compound concepts	Included	Barely included
	Chemistry terminology and calculation concepts	Included	Barely included
	Concepts related to specific types of substances	Included	Barely included
	Concepts related to specific types of processes	Included	Barely included
	Concepts about processes	Barely included	Included
	Concepts about technoscience	Included	Barely included
Statement forms		Action verb and meaning	Proposition
Conceptual levels		Greater focus on the macro level	Greater focus on the micro level
Learning progressions		Follows a good learning progression as a whole with fewer gaps	Follows a good learning progression as a whole with a few more gaps in each grade band

action verb defines a fundamental understanding requirement of it and the *meaning* refers to its specific content. Two *meaning* types have been identified in the CCCS. One is general statements that only refer to the names of chemistry core ideas, without explicitly indicating their meanings. For example, "knowing the law of conservation of mass; explaining quality relationships in the reaction". The other is specific statements that point out the final expectations of chemistry learning for students. For example, "knowing that atoms are made of a nucleus and electrons". Table 2 shows that chemistry core ideas in the NGSS are expressed in the *proposition* forms which directly present their specific meanings without action verbs. For example, "the total number of each type of atom is conserved in a reaction, and thus the mass does not change; each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons". It should be noted that the *Performance Expectations* section in the NGSS integrates scientific practices and core ideas, which uses *action verbs* to describe specific ways that students are expected to demonstrate their understandings (e.g., students who demonstrate understanding can develop and use a model to describe how the total number of atoms does not change in a chemical reaction and thus mass is conserved).[7]

From our perspective, each of the statement forms of chemistry core ideas in the two documents above has its own merits and inadequacies. Although the *action verb* included in the CCCS defines the fundamental requirement of chemistry core idea and provides a certain basis for teaching and evaluation, we must realize that some action verbs (e.g., know, understand) are cognitive and their corresponding behaviors are implicit. Therefore, it is difficult for most teachers and students to distinguish them, which may mislead teachers and students to pay more attention to the action verbs themselves instead of understanding the meanings of chemistry core ideas. Meanwhile, it is surprising that the CCCS only presents the names of some chemistry core ideas, with the absence of their specific meanings. Teachers with different experiences and abilities will, therefore, hold various understandings for chemistry core ideas, which can consequently influence students to understand and construct them. By contrast, the NGSS uses scientific languages to express the specific meanings of chemistry core ideas. These explicit statements highlight the interrelationships among concepts, which is helpful for teachers to gain the meanings of relevant concepts and their importance in chemistry easily. It is our recommendation that the subsequent curriculum standards revision should make reference to the statement forms in the NGSS in which chemistry core ideas are stated specifically and explicitly to provide more useful guidance to textbook compilation and chemistry teaching.

Conceptual Levels and Learning Progressions of Chemistry Core Ideas

In the CCCS, chemistry core ideas about *substances* place more stress on the macro level in grades 7−9, which is in favor of facilitating chemistry learning for beginners and motivating their interest in chemistry. In all three grade bands, great emphasis is attached to macroscopic ideas about *processes*, and slightly less emphasis in the molecule level and subatomic level, especially for energy and time dimensions (see Table 1). However, chemistry core ideas in the NGSS focus mainly on the micro level, especially in grades 9−12. We can see from Table 2 that nearly all ideas about *substances* and *processes* are at the molecule level and subatomic level. The conceptual levels in the NGSS imply that micro domain of chemistry core ideas should be reinforced in higher grades. From the above comparison, we may make further inferences that the CCCS seems to include more aspects of descriptive chemistry while the NGSS seems to put more emphasis on models and modeling.

One of the greatest challenges with the core ideas is ensuring a coherent and manageable set of standards,[7] that is, learning progressions. In general, the representation of chemistry core ideas in the CCCS and the NGSS follows a learning progression from macro level to molecular level to subatomic level as a whole. This arrangement implies the achievements and influence of recent research about learning progressions,[26−28] although many problems still worthy to be explored.[29] Further comparison of Tables 1 and 2 reveals that the progression of chemistry core ideas articulated in the CCCS seems more coherent and shows fewer gaps along different dimensions in moving from one level to another (e.g., chemical composition, structure, change and energy dimensions). In the NGSS, although chemistry core ideas follow a learning progression from the macro level and molecular level in grades 6−8 to the molecular level and subatomic level in grades 9−12, the learning progression in each grade band needs to be improved, especially in grade band 9−12 where chemistry core ideas are relatively weak in macro level. It is noteworthy that both the CCCS and the NGSS fail to provide well-defined progressions in the "state of matter" and "time" dimensions, with more gaps from one level to another (see above and bottom sections in Tables 1 and 2). These incoherence may be

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in part responsible for student learning difficulties. For example, ignoring time dimension of chemistry core ideas may block the learning of chemical equilibrium for students.[30] We suggest that teachers consider ways to enrich and supplement the chemistry curriculum based on their intensive understanding of chemistry knowledge. Table 3 summarizes the above comparisons between the CCCS and the NGSS.

■ DISCUSSION

The comparative analysis we have presented above indicates that there are certain differences in the representation of chemistry core ideas included in science education standards between China and the United States. Exploring the reason for these differences is important because it will help us understand chemistry core ideas better and ponder over the goals of science education. In particular, we elaborate on three aspects below as the major influential factors in the representation of chemistry core ideas in the two documents under analysis.

Different Research Perspectives on Science Education

From our perspective, one main reason why there are differences in content representation of chemistry core ideas is the different research perspectives on science education. American education researchers study and understand chemistry curriculum in the overall context of science education which focuses on the learning of cross-cutting concepts[31] and general concepts,[6,7,32] emphasizes STEM education,[33] and so on. Therefore, although chemistry is generally presented as a separate science course in high school, science education standards documents in American education classify science content knowledge into three major areas: physical sciences, life sciences, and earth and space sciences. In the NGSS, chemistry core ideas are mainly presented in the physical sciences, with slight references to the life sciences and earth sciences.[7] The interdisciplinary nature of the U.S. chemistry curriculum standards is an important aspect to know for teachers who are not necessarily chemistry specialists and it can contextualize the chemistry—an area that seems to be a deficit in the Chinese curriculum and in any other countries where chemistry curriculum standards are separate disciplinary curriculum standards. However, because of this interdisciplinary nature, it is hard to take chemistry core ideas into account comprehensively to some extent and a number of important chemistry concepts are missing from science education standards inevitably.

At present, Chinese curriculum still adopts the subject-based curriculum, and chemistry is a separate science discipline in school education. As noted above, the CCCS, as a separate disciplinary curriculum standards document, presents chemistry core ideas more systematically and highlights the characteristics of chemistry. However, for the same reason, it results in weak relationships between chemistry and other disciplines. It is our advice that Chinese chemistry teachers should pay more attention to the integration and connection among various concepts, consider the complementarity and mergence between chemistry and other disciplines, and guide students to learn and apply chemistry core ideas in the context of science, technology, and society.

Different Understandings of Chemistry Core Ideas

The differences in statement forms of chemistry core ideas between the two documents under analysis reflect the different understandings of chemistry core ideas. From the perspective of discipline ontology, disciplinary core ideas refer to the statements that summarize the most essential knowledge in a discipline possessing powerful interpretation,[1,10] while from the perspective of student learning, chemistry core ideas are also the panorama of science developed by students who put what they have learned together.[11]

In the NGSS, the *meanings* of chemistry core ideas are presented explicitly, without action verbs included. It can be inferred that researchers in the U.S. view chemistry core ideas as the summary and distillation of central chemistry knowledge, which reflects the assumption of discipline ontology to some extent. The Chinese educators focus more on students' understanding of chemistry concepts and specific knowledge from the perspective of student learning.[17] Therefore, statements in the CCCS take the form of *action verbs* which provide the basic understanding requirements of chemistry core ideas for students. However, the *meanings* of some core ideas in the CCCS only present the name without their specific content. These general and vague statements call for more thorough research on the meaning of chemistry core ideas from the perspective of discipline ontology.

Different Understandings of the Nature of Teaching Process

We hold the opinion that respective emphasis on the nature of teaching process in school education of China and the Unites States results in different conceptual levels and learning progressions of chemistry core ideas between the two documents. School education in China has always been guided by epistemology, which underlines that teaching process is a special cognitive process during which school teaching should follow a sequence from the shallower to the deeper and attach great importance to students' learning stage and development.[34] Affected by this, the CCCS has followed a relatively coherent learning progression, with chemistry core ideas presented from the macroscopic level gradually into the microscopic level (see Table 1). However, it seems that chemistry core ideas included in the CCCS focus more on the macroscopic level, with less attention paid to explanation and modeling on the molecular and subatomic level when compared to the NGSS. Therefore, we may argue that the CCCS falls short of fully representing the nature of chemical knowledge and the power of chemical thinking, which demands more reflection and discussion among chemistry educators.

The United States is a diverse country with various curriculum theories, such as subject-based curriculum theory, problem-based curriculum theory, student-centered curriculum theory[35] and multicultural education.[36] The collision and fusion of multiple theories affect the selection and presentation of curriculum. Table 2 implies that the influence of recent research results is not fully embodied in science education standards. It can be seen that the representation of chemistry core ideas in grades 9−12 in the NGSS is poor to some extent and there are many gaps in it with more focus on the molecular and subatomic characterizations. It does not deny that the ability of abstract thinking improves greatly with age. However, we question the focus mainly on the micro level in high school grades because research findings in science and chemical education show that students have serious difficulties in understanding and applying different assumptions of the atomic and molecular theories of matter.[37,38] Some chemistry core ideas, especially ideas in the micro level, such as molecular collisions, atomic rearrangements, and bond energies, are difficult to understand even for high school seniors. It is

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recommended that chemistry curriculum follow cognitive processes of students from analyzing the macro phenomenon of matter gradually into the explanation in its micro world.[5]

■ SUMMARY

We have analyzed and compared the representation of chemistry core ideas about *substances* and *processes* included in the CCCS and the NGSS. In general, the CCCS presents chemistry core ideas comprehensively and scientifically and has a good learning progression. However, we must acknowledge that many aspects of chemistry core ideas in the CCCS need to be improved. For the selection of teaching contents, more attention should be paid to the connection and integration between chemistry core ideas and other disciplinary ideas. For statement forms, specific meanings of chemistry core ideas are required to be presented explicitly and completely. For conceptual levels, when the macro levels are considered, the understanding of the micro level should also be reinforced at the same time. And for learning progressions, it is suggested that curriculum developers and teachers explore different levels of chemistry core ideas among different grades to improve the coherence of core ideas. Meanwhile, for the United States, chemistry core ideas included in the science education standards should emphasize more specific types of substances and chemical process, and more attention should be paid to the macro level of chemistry core ideas in order to achieve better learning progressions, which can certainly facilitate students' chemistry learning.

The differences in chemistry core ideas between the two documents reflect different perspectives on the goals of science education, the aims of chemistry, and expectations about quality teaching. We expect that our comparison and suggestions can inform chemical education and science education reforms not only for the U.S. and China, but also for other countries. And we also appeal for more focused attention and communication on the science education standards among different countries in order to prepare for scientifically literate future citizens—our common goal.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: bihualin@sdnu.edu.cn.

Notes

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