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THE THINKING OF STUDENTS AGED 15-18 IN EXPLAINING THE DISSOLUTION PHENOMENON

Guanxue Shi,
Shanshan Lu,
Hualin Bi

Abstract. *Explaining natural phenomena by determining causal relationships is conducive to understanding scientific concepts. In science education, numerous studies examine students' causal reasoning. Given the importance of core ideas for students' understanding of how and why a phenomenon occurs, the study focused on the relationship between students' understanding of atoms/molecules interactions and the nature of reasoning. This study drew on a framework that identifies essential components of students' reasoning, which was used to analyze the dissolution phenomenon in the example of salt in water. Students in grades 9-12 (N=147) explained the dissolution of salt. The results showed that there were five types of reasoning: simple descriptive, fuzzy causal, linear causal, interactive causal, and mechanistic. More students in higher than lower grades exhibited non-causal reasoning. Based on the students' drawings of atoms/molecules interactions, the study summarized performance in the association category. Students' performance in drawing indicated that their understanding of particle interactions was limited. The results showed that there was a large correlation between understanding of the core ideas and reasoning types.*
Keywords: *core ideas understanding, causal reasoning, dissolution phenomenon, small-sample qualitative study*

Guanxue Shi, Shanshan Lu, Hualin Bi
Shandong Normal University, China

Introduction

Causal reasoning has long been the subject of debate and criticism among philosophers and scientists. In science education, as a crosscutting concept, cause and effect (mechanism and explanation) helps students to construct explanations from the internal causal perspective (National Research Council [NRC], 2012). Currently, constructing explanations of natural phenomena has been listed as an important scientific practice by national curriculum standards (e.g., NGSS Lead States, 2013), in which students need to use core ideas to understand how and why the phenomenon occurs, to establish logical causal relationships presented at an appropriate level of representation (De Andrade et al., 2019). Numerous studies have examined students' causal thinking (Moon et al., 2016; Moreira et al., 2019a; Weinrich & Talanquer, 2016). However, there are significant challenges in constructing causal reasoning for chemical phenomena that are particularly well documented in students at different levels of education (Moon et al., 2016; Moreira et al., 2019a).

In chemistry curricula, dissolution is a common phenomenon (e.g., sodium chloride dissolves in water) that students have difficulty understanding (e.g., Çalýk et al., 2005; Devetak et al., 2009; Naah & Sanger, 2013). Learning the related concepts does not necessarily imply that students can use them for explaining the dissolution phenomenon, which can be further explained by discussing the relationship between "understanding theories (UT)" and "understanding phenomena (UP)" (McCain, 2015). UT is a necessary and not sufficient condition for UP. Two learners with the same knowledge may exist with different phenomena because they have different capacities for the necessary UT (McCain, 2015). Mechanistic understanding of the dissolution phenomenon is closely intertwined with the ability to utilize the core idea - the interactions of atoms/molecules (NRC, 2012; Cooper et al., 2017a). For upper-secondary school students, treating chemical bonding as a continuum of electrical forces is effective to explain how the dissolution phenomenon occurs, which could improve the understanding of the way that atoms interact (Levy et al., 2007). In addition, students need to understand 'how do particles combine to form the matter' and 'how do different matters interact with each other'.

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Domain-specific knowledge related to these questions is taught in chemistry courses at different grade levels in China. Causal reasoning affects students' capacity to incorporate knowledge into existing conceptual structures as they construct explanations (Uzuntiryaki & Geban, 2005). Learners who cannot adequately understand causal processes would oversimplify their understanding (Taber & García-Franco, 2010). However, few studies focus on the role of the core ideas in students' reasoning process. Considering this, the study focused on students' causal reasoning and conceptual understanding of the dissolution phenomenon from the perspective of atomic/molecular interaction, aimed at exploring the relationship between students' understanding of atoms/molecules interactions and the nature of reasoning.

Explanation and Causal Reasoning

The process of constructing explanations has been explored by philosophers of science for years. The existence of five models of scientific explanation (i.e., covering law, statistical-probabilistic, causal, pragmatic, and unification) reflects the fact that there is no unitary theory of explanation in the philosophy of science (Braaten & Windschitl, 2011). But philosophers of science generally agree that explanations should provide theoretical accounts of how phenomena unfold the way they do. Salmon (1978) suggested that explanatory power would be enhanced when explanations offer the causes of underlying phenomena. Learners can explain a phenomenon through laws and principles without paying attention to causality. For example, when the temperature of the gas is constant, the volume of the gas is compressed and the pressure in the container will increase. Using the ideal gas law to explain this process is not causal reasoning. If the explanation mentions the movement of molecules and the collision between molecules and the wall of the container, it is a causal process (Alameh & Abd-El-Khalick, 2018). Although causal reasoning has long been debated by philosophers and scientists, causality is currently considered an essential category of thinking for explaining natural phenomena (Besson, 2010). In particular, 'mechanism' is central for the philosophical understanding of the sciences (Machamer et al., 2000; Russ et al., 2008). The most complex causal reasoning is named mechanistic reasoning. It articulates the progress of how the properties of components determine the interactions of entities, which in turn affect their activities and spatial distribution (Machamer et al., 2000; Russ et al., 2008; Talanquer, 2018).

It is a challenging task to apply the theories in the philosophy of science to science education. The term 'explanation' is used in two different ways: explication and scientific explanation (Braaten & Windschitl, 2011; Brigandt, 2016). The difference between them is that the latter pertains in some mental content, such as a concept or one's reasoning (Brigandt, 2016). However, there was a lack of deep analysis on the meaning of explanation in scientific education. For example, in the *Next Generation Science Standards* (NGSS Lead States, 2013), there are three ways to use: as a goal for science, as a tool for learning about science, and as a way of answering scientific questions. But the NGSS does not offer any conceptualization of the meaning of explanation (Alameh & Abd-El-Khalick, 2018).

What is an explanation in science education? The concept of 'explanation' is essentially a tentative answer to a scientific question, invoking reasoning to find a logical reason for a factual outcome to answer three questions of what, how and why (Osborne & Patterson, 2011). The importance of construing explanations lies in improving students' conceptual understanding and facilitating learning about the nature of scientific knowledge (McCain, 2015). Currently, more frameworks use explanations as evidence to assess students' conceptual understanding and reasoning (Taber & Watts, 2000; Weinrich & Talanquer, 2016; Yan & Talanquer, 2015). What are the evaluation criteria for a good explanation? The first thing to make clear is that a good interpretation is not a correct one (Taber & Watts, 2000; Weinrich & Talanquer, 2016). De Andrade and colleagues (2019) suggest these four key elements of a good explanation: relevance, conceptual framework, causality, and the appropriate level of representation. The first two elements are used to delete non-explanations, and the last two elements are used to characterize the quality of the explanation. To provide a high-quality explanation of a chemical phenomenon, the sub-microscopic level is essential. Another important aspect is the validity of the reasoning. Reasoning is considered a core component in the existing framework of explanations (Tang, 2016; Yao & Guo, 2017). Constructing explanations is becoming an important practice to explore students' reasoning.

Because science generally seeks to answer why a particular phenomenon occurs, science education focuses on students' causal reasoning in the practice of constructing explanations (Osborne & Patterson, 2011). Considering reasoning as the implications of a series of successive sentences (Tang, 2016), researchers currently prefer to divide students' responses into smaller units and then determine the reasoning underlying each unit.

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The types of reasoning are determined by identifying the relationships between the components (Metz, 1991; Russ et al., 2008; Weinrich & Talanquer, 2016). Several studies have confirmed that students used many types of reasoning in constructing explanations (Becker et al., 2016; Cooper et al., 2016; Moreira et al., 2019a). There exists a problem of using the same term to denote different mechanisms in reasoning types. For example, the relational reasoning mentioned by Sevian and Talanquer (2014) emphasizes that a phenomenon is the result of a single entity. However, the relational reasoning proposed by Zangori and colleagues (2020) emphasizes that the cause of the phenomenon is two entities. The main reason for the difference in meanings is that the current framework is ambiguous in determining causality. In addition, research showed that young students can show different types of reasoning (e.g., relational reasoning, simple causal reasoning, mechanistic reasoning), but the instruction may make students lose their original complex reasoning (Moreira et al., 2019b; Russ et al., 2008). Considering these, more work is still needed in science education.

Understanding about Dissolution Process

When a substance dissolves, the interactions between particles cannot be directly observed or experienced. Counterintuitive information may be assimilated into students' initial concepts, creating misconceptions (Vosniadou, 1992). For example, when sucrose dissolves, the solution at the bottom of the vessel may be darker than at the top, leading students to assume that the sucrose concentration is greater at the bottom than that at the top. Studies of dissolution about misconceptions have primarily focused on the nature of dissolution, the existing form of particles, and related concepts, such as bonds and energy (e.g., Abell & Bretz, 2018; Devetak et al., 2009; Taber & García-Franco, 2010). Such misconceptions provide an empirical basis for the process of conceptual change.

Few studies have gone beyond specific knowledge to reveal students' understanding from the core ideas level. Currently, the main understanding of the interactions between particles included the notion that ionic compounds exist in solution as molecules and react with water through an acid-base reaction (Naah & Sanger, 2013); that bond breaking may be due to external forces, such as heat, stirring, and the impact of water (Abell & Bretz, 2018; Lu et al.,2019; Smith & Nakhleh, 2011; Taber & García-Franco, 2010); and when two substances are mixed, the solvent does not play a role (Smith & Nakhleh, 2011). These ideas reflect the students' lack of understanding of the interactions involved in dissolution. Actually, one of students' main difficulties is in utilizing sub-microscopic explanations to visualize and represent the dissolution phenomenon (Çalýk et al., 2005). It would be helpful to understand the dissolution phenomenon by improving students' understanding of the particle nature of matter (PNM), the interactions between particles and the ability to develop explanations at the macro, micro and symbolic levels (Smith & Nakhleh, 2011; Taber & García-Franco, 2010). These would provide a guarantee for core ideas to connect fragmented knowledge.

Research Questions

As noted by Vosniadou and Ioannides (1998), fragmented concepts need to be embedded in complex conceptual structures for greater explanatory power. Changes in conceptual structure denote differences in conceptual understanding, which affect the construction of core ideas (Wan & Bi, 2016). In addition, reasoning affects one's capacity to incorporate knowledge into existing conceptual structures. Therefore, this study focused on students' reasoning and conceptual understanding of the dissolution phenomenon from the perspective of atomic/molecular interaction. In China, students in different grades learn different concepts. Accordingly, when explaining how a substance dissolves in water, students of different grades may use different terms, but researchers in this study expect them to realize that there is an interaction between solute and solvent particles. The study addressed the following three research questions:

1. What are the different types of reasoning upper-secondary school students use to explain the dissolution phenomenon?
2. What are the differences in reasoning among students in different grades?
3. To what extent does students' understanding of the interactions of atoms/molecules impact their reasoning types?

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A Framework for Analyzing Types of Reasoning

In 2003, Grotzer developed a taxonomy of causal models to characterize a range of levels of reasoning. However, it is difficult to apply the different dimensions directly to the analysis of reasoning on specific topics. To improve operability, there are researchers who have done further work (e.g., Russ et al., 2008; Sevian & Talanquer, 2014). By integrating the work of several researchers, Moreira and colleagues (2019a) proposed an analytical framework for identifying the students' reasoning. The study adopted this analytical framework to clarify the procedures for identifying different reasoning.

The first step in the reasoning process is to identify the entities causing the phenomenon. A phenomenon may be directly caused by one or more entities, or it may be caused by the cumulative effect of entities (Grotzer, 2003). The second step is to identify the interaction pattern. In other words, it needs to describe the different relationships between causes and effects. The interaction pattern includes simple linear causality, multiple linear causality, mediating cause, interactive causality, re-entrant causality, and constraint-based causality. Finally, it needs to identify why the entities enable the phenomenon to occur. The process that triggers causality is called a mechanism, which involves the function of an entity, results, or implicit entities, properties, and rules to explain the phenomenon. Therefore, identifying the cause (What), interaction pattern (Why), and process (How) are the three procedures for identifying different reasoning.

To determine the types of reasoning used when students explain the dissolution phenomenon, this study followed the following theoretical basis. Reasoning that identifies only the cause of the dissolution was considered non-causal reasoning. Reasoning that identifies the pattern of interaction was considered causal reasoning. Mechanistic reasoning can identify the process, focusing on temporal changes in structures, properties, and activities, as well as spatial aspects of an organization (Krist et al., 2019). To analyze the reasoning in an explanation, it can be broken down into its various components. The process dimension focuses on the relationships among entities, properties, activities, and the organization. Align with the four components proposed by Moreira and colleagues (2019a), this study was based on them to identify the reasoning units, as follows:

Entities (E): Objects that affect the occurrence of a phenomenon (e.g., sodium chloride, water molecules);

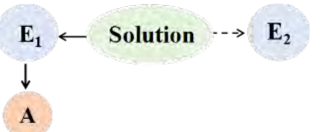
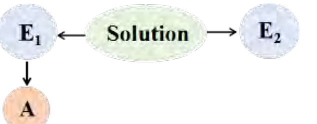
Activities (A): Behaviors that cause changes in entities, with special emphasis on activities that take place between entities (e.g., motion, diffusion, collision);

Properties (P): Specific properties that affect the activities of entities (e.g., charge, electrolyte, ionic crystal, solubility);

Organization (O): The spatial form of entities (where they are located, and how they are organized; e.g., hydrated ion).

By identifying these components and three procedures, the five types of reasoning were determined (see Table 1). The study also mapped the contents involved in three procedures with the help of reasoning diagrams to distinguish different types of reasoning readily.

Table 1
The Types of Reasoning Involved in Explaining the Dissolution Phenomenon

Types of Reasoning	Performance	Reasoning Diagram Example
Simple descriptive	An entity is identified as the cause. Focuses on describing the properties, activities, or organization of the entity.	
Fuzzy causal	Two entities are identified as the cause. No interaction between entities. No causal relationship.	

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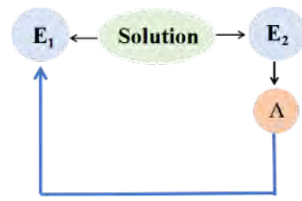
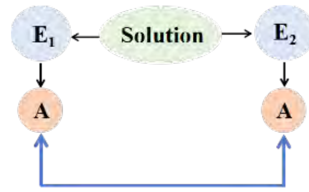
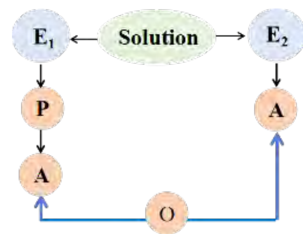
Types of Reasoning	Performance	Reasoning Diagram Example
Linear causal	Two entities are identified as the cause. The interaction pattern between entities is linear. There is no causal relationship between the properties, activities, or organization of entities.	
Interactive causal	Two entities are identified as the cause. The interaction pattern between entities is two-way. There is no causal relationship between the properties, activities, or organization of entities.	
Mechanistic	Two entities are identified as the cause. The interaction pattern between entities is two-way. Reasoning begins with the structure of the entities, considering that the properties affect the activities, and the activities affect the organization.	

Note. E ←: *The solid black line pointing to the entity (E) represents the cause identified.* →: *The solid blue line represents the pattern of interactions among the entities. The properties (P), activities (A), and organization (O) of the entities involved in the process are connected in sequence by directed arrows in order of presentation. The properties, activities, and organization are not necessarily involved in the student's reasoning process simultaneously.*

Research Methodology

General Description

Students offer richer explanations and conjectures in familiar contexts (Linn, 2013). This study used qualitative methods to obtain the performance of Chinese students in grades 9-12 in both causal reasoning and conceptual understanding of the dissolution phenomenon when explaining the phenomenon of salt being put into water. Upper-secondary school students were given a task at the end of the 2019-2020 academic year. To avoid parroting knowledge, more than three months had passed since the students had learned the relevant concepts. They were asked to provide a written explanation combined with a drawing. Their written explanations can be used to analyze thought processes (Grimberg & Hand, 2009). Drawing can contribute to logical reasoning and learning concepts, which allows researchers to observe how students are thinking about the process (Ainsworth et al., 2011; Cooper et al., 2017b; Tytler et al., 2020). Drawing in combination with writing is conducive to sharpening students' attention to causality and conceptual understanding (Kang et al., 2014).

Participants

169 students aged 15-18 years from four grade levels participated in the study, all of whom have been taught the nature of the forces between charged particles in physics classes. Students in grade 9 (aged 15~16) begin chemistry classes. Fragmented knowledge is taught in different grades (see Table 2). Although students are taught by specialized chemistry teachers, they are rarely intentionally guided by their teachers to integrate the related concepts. The study selected students from regular classes in upper-secondary schools so that the test results would represent the widest possible range of reasoning performance and the understanding of the interactions of atoms/molecules. On account of the practical benefits of convenience sampling, one regular class was selected in each grade in Shandong province. The initial sample size could be found in Table 2.

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Table 2
The Information About the Participants

Sample	Initial sample size	Effective sample size			Chemical knowledge
		Written explanation	Drawing	interview	
Grade 9	42	39	36	7	Students are taught that Na+ and Cl- exist in a solution.
Grade 10	39	35	35	7	Students learn about bonding (covalent and ionic).
Grade 11	48	38	36	7	Students receive lessons on the structure of matter (water is a polar molecule).
Grade 12	40	35	35	7	Students learn no new concepts related to dissolution.
Total	169	147	142	28	

Instrument

The English version of the task is given below, which is translated from the original Chinese.

Add a small amount of table salt to a beaker of water. Let the beaker stand until the salt has completely disappeared. Explain the following: What is the process of the above phenomenon? Draw a picture to support your explanation, showing what is happening inside the beaker.

Before the test, four chemistry teachers and postgraduates with a chemistry degree were asked to evaluate the instrument. They evaluated whether the linguistic expression was ambiguous and whether the test task was appropriate.

Data Collection

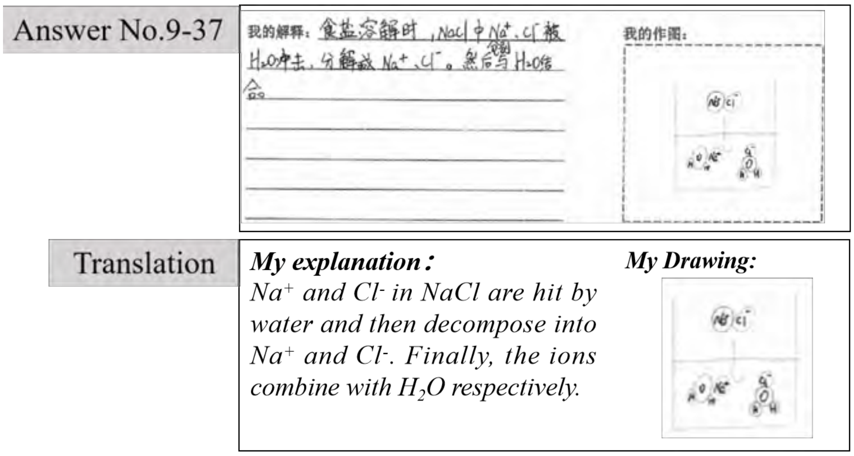
All students, their parents, teachers, and principals agreed to voluntarily participate in the study. Students were informed of the purpose of the test and agreed to voluntarily participate in the study. Teachers told students that the test would not affect course grades and encouraged them to give full play to their imagination. As the students had already learned about salt dissolving in class, a questionnaire was presented directly to them. All questionnaires were completed in class. After completing the questionnaire, seven students from each grade were randomly interviewed. The questionnaires answered by the students were used as interview foci. The interviewer asked students individually to explain what they had written and drawn, which constitutes triangulation, used to increase research validity. To capture the students' understanding of the interactions, the interviewer then asked primarily about the role of water and sodium chloride in the dissolution process. Each interview lasted approximately fifteen minutes, and transcripts of the interviews were made from the audio recordings. According to the criterion of explanation (De Andrade et al., 2019), the questionnaires without explanation were not analyzed. Table 2 lists the information for the effective sample size.

Data Analysis

To analyze the data, students were coded by grade level. For example, the code '9-37' denoted data collected by a grade 9 student with ID number 37, while the code 'I10-1' denoted data collected by a grade 10 student with ID number 1 during the interview. The analysis of all written and drawn data consisted of two steps to determine the type of reasoning. Drawings were used to identify the components not present in the written explanations (e.g., organization). The first was building the initial coding of entities, properties, activities, and organizations. An example is shown in Figure 1.

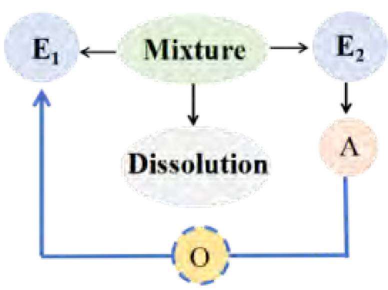
https://doi.org/10.33225/jbse/23.22.337

Figure 1
An Example Response



This student numbered 9-37 indicated that NaCl and H_2O were two entities, mentioned the activity (hit) and the organization (ions combine with H_2O). No extra components were provided in the drawing. The response was therefore coded as involving three components: entities, activities, and organization. The second step was determining the types of reasoning according to the three procedures. In the example shown in Figure 1, the student mentioned that 'Na$^+$ and Cl$^-$ in NaCl are hit by water', indicating he thought that both the salt and water were the entities and the water acted in one direction on NaCl, showing a linear relationship. There was no causal relationship between the activity (hit) and the organization (ions combine with H_2O) regarding the process dimension. The reasoning was linear causal, as illustrated in Figure 2.

Figure 2
Reasoning Diagram Corresponding to the Explanation in Figure 1



Note. NaCl (E_1) and H_2O (E_2) are identified. The solid black arrow pointing to the entities indicates that both entities are the cause of the dissolution. The blue arrow indicates the unidirectional effect of the activity (A) of E_2 on E_1. There is no clear cause-and-effect relationship between the activity (A) and the organization (O), as indicated by dotted lines.

Initially, approximately 25% of the sample was analyzed, with initial coding of explanatory components. The first author and two graduate students analyzed the students' responses, which were categorized according to the initial coding. To ensure the reliability of the data, three researchers discussed all instances of disagreement to arrive at a consensus. The first author and one graduate student then extracted 28% of the sample to code. The kappa value was 0.845. After discussing any discrepancies again, the first author coded the remaining 47% of the sample. All recordings were transcribed verbatim into a Microsoft Word document by the first author. The same coding steps yielded results that were consistent with the written explanations. Due to space limitations, the responses to the first question in the results section were presented only with the student's written description.

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To answer the second question, the number of reasoning subtypes was summarized after coding. Then, the number of students who exhibited different subtypes of reasoning was counted. Finally, differences among grades in reasoning were analyzed using Fisher's exact test. Bonferroni correction was used for pairwise comparisons.

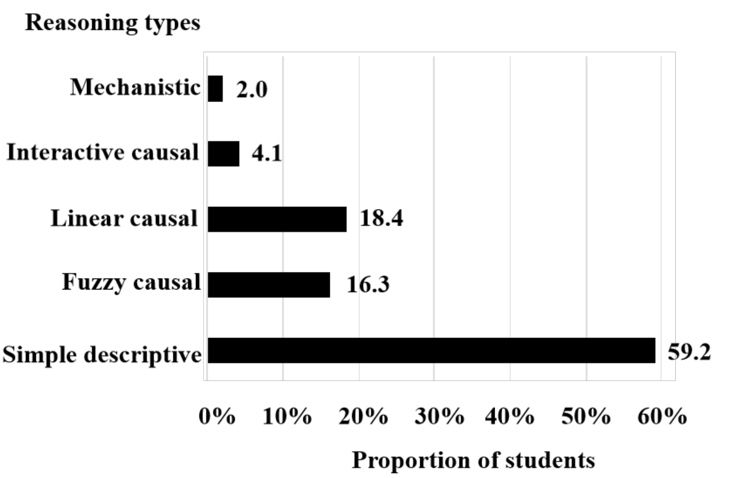
The drawings serve as an effective support to analyze students' understanding of interactions between atoms/molecules. According to the analytical framework for student-generated drawings (Tang et al., 2019), all authors unanimously decided to collect students' performance in the association category. The connection between entities in the drawing helped identify the key features to understand the interactions between particles. For inter-rater reliability, the first author and one graduate student extracted 50% of the sample to code. For example, in the drawing in Figure 1, water and Na^+ or Cl^- were joined together through touching boundaries, which was coded as an adjoining subcategory. The association category was divided into three subcategories: unpresented, independent, and adjoining. Then two researchers re-coded students' drawings until they achieved an agreement of 100% on the coding. The first author coded the remaining samples. The percentage of students in the different subcategories was then calculated. Fisher's exact test was used to calculate the correlation between the understanding of the core ideas and types of reasoning.

Research Results

Types of Reasoning Used to Explain Salt Dissolving

The proportion of upper-secondary school students exhibiting different types of reasoning is shown in Figure 3. Almost three-fifths of the students explained the phenomenon with simple descriptive reasoning. Of the students, 16.3% thought that NaCl and H_2O were the cause of the dissolution, but they were not clear about the interaction pattern involved. Of the explanations, 18.4% explicitly mentioned that the activity of H_2O caused salt dissolving. Fewer than 5% of students recognized the existence of two-way interactions, while 2.0% used mechanistic reasoning and explained salt dissolving from the perspective of 'structure-property-activity'. Based on the specific performance, the characteristics of each type of reasoning used to explain salt dissolving were then summarized.

Figure 3
Distribution of Five Types of Reasoning



Most students (59.2%) used simple descriptive reasoning. They generally explained the phenomenon of salt being put into water based on their daily life experience (e.g., the particles gradually disappeared) or a small number of concepts (e.g., NaCl ionizes into Na^+ and Cl^-). All identified salt as the cause of the dissolution. This type of reasoning could be divided into four main subtypes (see Table 3). Some students (21.8%) mentioned only that the entity that caused the dissolution was the salt itself. Students identified activity (21.8% EA), although the activity mentioned was the spontaneous action of salt, leading to many similar explanations, such as '*salt dissociates into*

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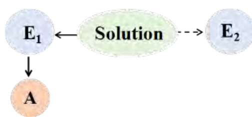
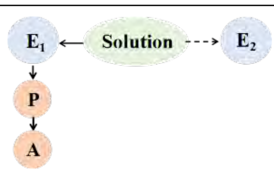
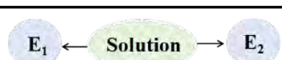
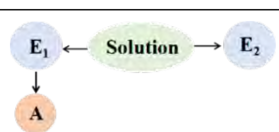
Na^+ and Cl^-. Of the students, 7.5% considered that the reason for the dissolution lay in a property of NaCl (NaCl is an electrolyte with ionic bonds). EPA (6.8%) represented the integration of EP and EA. In this case, properties (electrolyte, with ionic bonds) and NaCl activities (ionization, broken bonds) were mentioned. However, there was no causal logical relationship between the properties and actions. Associated students' drawings only showed that NaCl was present in the solution as Na^+ and Cl^-.

Table 3
Examples of Simple Descriptive Reasoning

Components	Reasoning diagrams	Representative responses
E		a. *Salt changes into Na^+ and Cl^-.*
EA		b. *Salt dissociates into Na^+ and Cl^-.*
EP		c. *NaCl is an electrolyte, so it dissolves in water.*
EPA		d. *NaCl is an electrolyte. It ionizes in water.* e. *In NaCl, ionic bonds are broken, and Na^+ and Cl^- are formed.*

Almost 16% of the students were aware that water is also an entity that causes dissolution, but they were not aware of the specific interaction pattern between salt and water. This type of reasoning could also be divided into four main subtypes: 6.1% E, 2.7% EP, 4.8% EA, and 1.4% EAO (see Table 4). Similar to the simple description, students were more likely to mention the properties (e.g., electrolyte, ionic crystals) and activities (e.g., ionization, broken bonds) of NaCl, while they were less likely to mention the activities of water. Students knew that Na^+ and Cl^- are closely arranged in the salt solid. After being placed in water, the students knew that salt dissociated into ions. They recognised water also played a role in the dissolution process, but they were not clear about the interaction pattern. Moreover, the causal relationship involved could not be clearly stated. As student 12-4 (see i in Table 4) mentioned, he did not provide a reason for the activities (water is separated from hydrated ions) and the organization (form hydrated ions with water). He represented a group of students who were not clear as to why NaCl became Na^+ and Cl^-.

Table 4
Examples of Fuzzy Causal Reasoning

Components	Reasoning diagrams	Representative responses
E		f. *Na^+ and Cl^- form when solid sodium chloride meets water.*
EA		g. *Salt ionizes in water. Na^+ and Cl^- combine with H_2O.*

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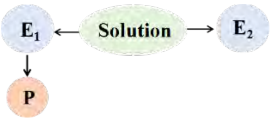
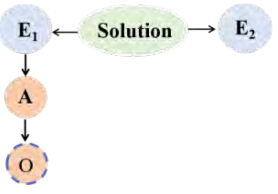
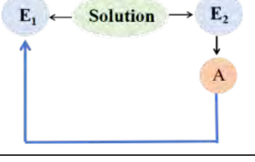
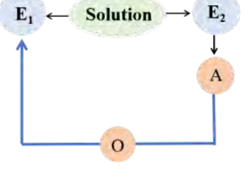
Components	Reasoning diagrams	Representative responses
EP		*h. The force between Na^+ and Cl^- in NaCl is small, so NaCl will dissolve in water.*
EAO		*i. After NaCl enters the water, ionic bonds are opened. They form hydrated ions. Over time, water is separated from hydrated ions, leaving Na^+ and Cl^-.*

Less than one-fifth of the students showed linear causal thinking. These students not only identified the two entities but also considered the pattern of interaction. They tended to believe that the water was the primary cause of the dissolution. This type of reasoning can be divided into two subtypes: EA (9.5%) and EAO (6.1%). Most of the activities mentioned were activities of water, such as 'impact', 'split', and 'hit'. The properties of entities were rarely mentioned. Reasoning involving only entities and activities (EA) generally expressed that dissolution was the result of water hitting NaCl, then NaCl ionizing into Na^+ and Cl^-. The performance of students 9-15 (see j in Table 5) was representative of a group of students. In contrast to fuzzy causal reasoning, these students are more likely to show the organization in which Na^+ and Cl^- combined with H_2O. However, they failed to express the cause. There was no mention of time-related effects and no expression of causal relationships.

Table 5
Examples of Linear Causal Reasoning

Components	Reasoning diagrams	Representative responses
EA		*j. After NaCl is put into H_2O, H_2O splits NaCl into smaller particles from the outside.*
EAO		*k. Water molecules split salt into Na^+ and Cl^-.*

Of the students, 4.1% felt that the pattern of interaction between the entities was not unidirectional, but rather bidirectional (see Table 6). These students failed to describe certain processes from a structure-property perspective. This type of reasoning could also be divided into two subtypes: EA (2.7%) and EAO (1.4%). The explanation given by students numbered 11-37 was a typical example of EA (see l in Table 6). He explicitly mentioned the interaction pattern between H_2O and NaCl. However, the student did not mention why entities 'collide'. No causal relationship was found between activities and organization. Consistent with student 10-8's response (see m in Table 6), most students did not know why H_2O combines with ions to form the final organization.

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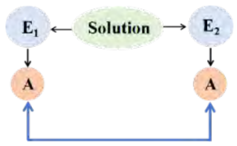
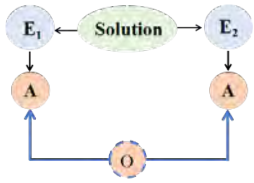
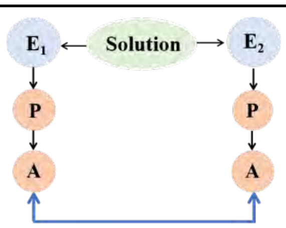
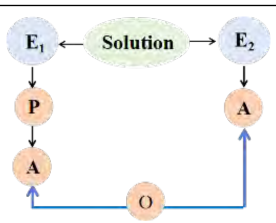
Table 6
Examples of Interactive Causal Reasoning

Components	Reasoning diagrams	Representative responses
EA		*l. Na^+ and Cl^- form NaCl through electrostatic attraction. Because of the interaction between the H_2O and NaCl, NaCl dissolves in water.*
EAO		*m. Na^+ and Cl^- gradually separate. Water molecules combine with Na^+ and Cl^-.*

By focusing on the entities that induced the phenomena and their interaction pattern, 2.0% of students could explain the specific dissolution process. Students who think mechanistically paid attention to whether the causal sequence of structure-property-activity was fulfilled. The response of the subject numbered 10-11 (see n in Table 7) gave the specific dissolution process. He stated that the structure of H_2O (different charges accumulate at each end) and the property of NaCl (with ionic bond) caused them to interact. The potential theoretical support was the attraction of charges of opposite polarity. The result was that the ionic bond was broken. Unfortunately, the student's drawings did not present the organization at the micro-level. Students 9-18 also exhibited strong causal logic (see o in Table 7). He indicated that the organization was affected by the activities of NaCl (combined with H_2O) and H_2O (taken away by H_2O), and the activities were affected by properties (different charges attract each other). Those explanations were not the most scientifically correct, but the reasoning process exhibited complex causality.

Table 7
Examples of Mechanistic Reasoning

Components	Reasoning diagrams	Representative responses
EPA		*n. The positive and negative charges accumulate at both ends of water molecules, which interfere with the ionic bonds in NaCl, making them unable to exist stably.*
EPAO		*o. NaCl is made up of Na^+ and Cl^-. They cannot recombine in an aqueous solution to form a solid, so it should combine with H_2O. Therefore, the process of salt dissolving is Na^+ and Cl^- are taken away by H_2O.*

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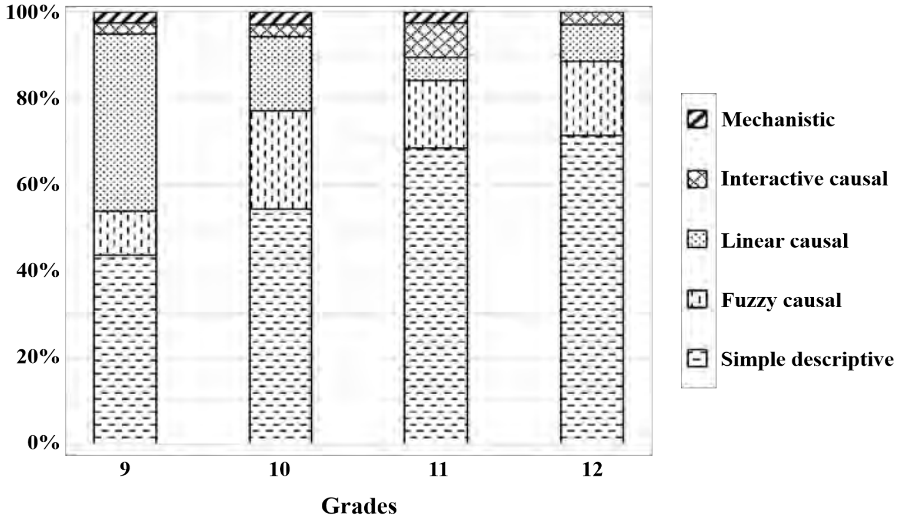
Differences in Reasoning of Students in Different Grades

Figure 4 shows the distribution of different types of reasoning among grades. The percentage of 11th and 12th graders who exhibited simple descriptive reasoning was significantly higher than 50%. The prevalence of fuzzy causal reasoning did not differ markedly among grades, although 10th grade accounted for the highest proportion of this type of reasoning. Grade 9 students showed a significantly higher proportion of linear causal reasoning than did other grades. Eleventh graders exhibited a slightly higher proportion of interactive causal reasoning. With increasing grade, the proportion of simple descriptive reasoning increased gradually, while that of linear causal reasoning decreased gradually. A change in the linear causal reasoning trend appeared as an inflection point in grade 12. The smallest proportion of responses exhibited mechanistic in each grade.

Figure 4
Distribution of Reasoning Among Grades



Differences among four grades in the five types of reasoning were analyzed. Fisher's exact test indicated a significant association between grades and reasoning types ($\chi^2_{(N=147)} = 22.256$, $p = .011$; Cramer's $V = .234$). According to the standards for interpreting Cramer's *V* proposed by Cohen (Gravetter & Wallnau, 2004), the results indicated a moderate correlation between grades and reasoning types. There was a significant difference in reasoning types between 9th and 11th grade ($\chi^2_{(N=77)} = 14.988$, $p = .002$) and between 9th and 12th grade ($\chi^2_{(N=74)} = 12.082$, $p = .006$).

The Impact of Students' Understanding of the Interactions on Reasoning Types

The students' understanding of the interactions between atoms/molecules was mainly reflected in the association category in their drawings. A percentage of 40.1% of the students did not represent how these shapes were related in their drawing. 49.3% believed that sodium chloride exists independently as ions in solution. 10.6% thought that Na^+ and Cl^- would combine with water, existing in the form of adjoining (touching boundaries) in the drawing. Figure 5 shows the students' reasoning types in the association category. From the unpresented, independent to adjoining subcategory, the proportion of simple descriptive thinking gradually decreased, while the proportion of linear causal thinking and interactive causal thinking gradually increased. Reasoning types were most prevalent in the adjoining subcategory.

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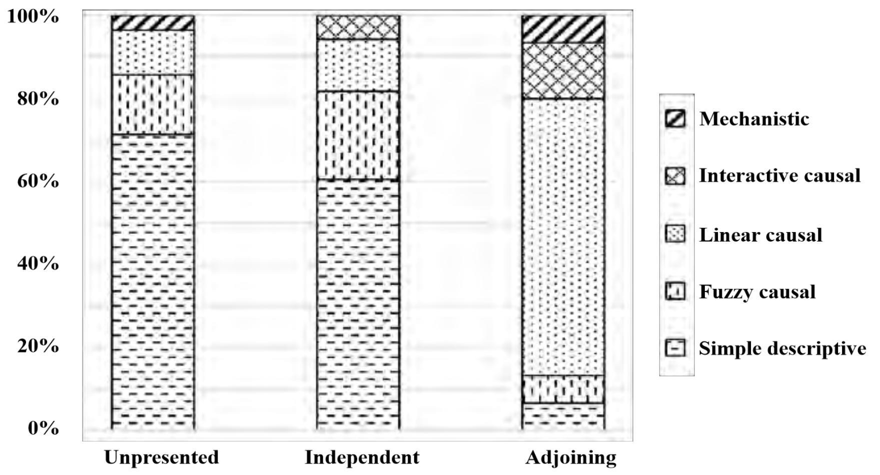
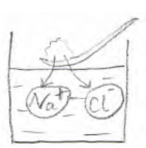
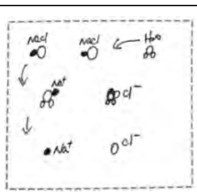
Figure 5
Distribution of Reasoning in Association Category



Using Fisher's exact test, the data indicated a large correlation between the understanding of the interactions and reasoning types ($\chi^2_{(N=142)} = 35.101$, $p < .0001$; Cramer's $V = .378$). Students' drawing examples in the category of association are in Table 8. 40.8% of students did not represent any association between entities. Of these, 70.2%, 14.0%, 10.5%, 1.8%, and 3.5% represented five reasoning types from simple description to mechanism, respectively. They all used macroscopic perspective to present the change process of sodium chloride solid from large to small by drawing. In the independent subcategory, students (48.6%) thought that Na^+ and Cl^- were not joined together. Specifically, 40.5% of the students with a macro-micro perspective used circles for sodium chloride and wavy lines for water. 59.5% of students with a microscopic perspective directly represented different ions or molecules with different circles. These students generally had no idea of the role water plays in the dissolution process. The percentage of non-causal reasoning was 82.6%. 10.6% of the students represented that the ions and water were connected by touching boundaries. But in the specific organization, there were two types: ions (Na^+ and Cl^-) and atoms (hydrogen and oxygen) were randomly or directionally joined together. Students who drew directional organization understood that touching boundaries represent the opposite charges attract, using mechanistic reasoning.

Table 8
Drawing Examples with Different Reasoning Types

Types of reasoning	Students ID	Examples of the drawing	Association sub-categories
Simple descriptive	9-34		Independent
Fuzzy causal	12-4		Independent

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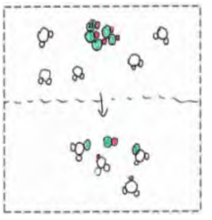
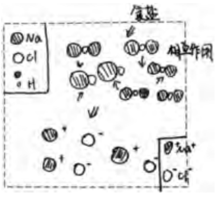
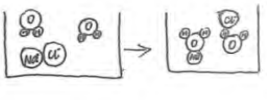
Types of reasoning	Students ID	Examples of the drawing	Association sub-categories
Linear causal	10-15		Adjoining
Interactive causal	11-37		Independent
Mechanistic	11-5		Adjoining

Reasoning was difficult to determine directly from students' written explanations because it was not clear and logical. The interview data were used as supplementary evidence. The study took simple description reasoning and fuzzy causal reasoning as examples.

Interviewer: Can you explain more specifically what happened when NaCl dissociates?

I9-34 (See b in Table 3 and Table 8): This is the spontaneous behavior of NaCl. Since NaCl is a strong electrolyte, this property means that it will dissociate.

Interviewer: Why is that? What role does water play?

I9-34: Water just provides a system environment and does not play a role.

Interviewer: Would you predict that NaCl would dissolve in ethanol or carbon tetrachloride?

I9-34: No matter what the solvent is, NaCl will dissolve. This is determined by its own properties.

The results of the interview showed that students who used simple descriptive thinking did not recognize the existence of interactions between solution and solvent and instead emphasized the existence of an active entity. Students who used fuzzy causal thinking recognized the role of water, but they were unaware of the interaction pattern between entities.

Interviewer: Can you explain the process by which NaCl breaks ionic bonds?
I12-4 (See i in Table 4 and Table 8): Water molecules are in constant motion. The ionic bonds are broken by the action of water molecules.
Interviewer: What does 'action' mean?
I12-4: I don't know how H_2O affects NaCl.
Interviewer: Why does water combine with the ions and then separate in your drawing?
I12-4: I think water molecules should play a role in the dissolution of sodium chloride, but I don't know. The reason why they go back to the ionic state is that I remember they are in this form in solution.

Through the analysis of the drawing and interview data, the students' reasoning types corresponded to their understanding of the interactions of atoms/molecules. Students' understanding of the interactions could be sum-

https://doi.org/10.33225/jbse/23.22.337

marized as follows: (1) There are no interactions between entities; (2) There is an interaction between entities, but it is not clear what it is; (3) Entities interact with each other with varying degrees of activity; (4) The interaction consists of collisions between entities that are in constant motion; and (5) The interactions are determined by the microscopic structure of the entities.

Discussion

Differences in Five Types of Reasoning about Dissolution Phenomenon

Students presented diverse reasoning when explaining salt dissolving. Nearly 60% of students identified only one entity as the cause, using simple descriptive reasoning. Existing studies of reasoning showed that for most students, reasoning ability was at a relatively low level (Moon et al., 2016; Moreira et al., 2019a). Although reasoning could be taught by teachers (Cracolice et al., 2008), participants in this study were not explicitly guided in causal reasoning during daily instruction. Moreover, the understanding that the interactions between atoms/molecules are essentially the force between charged particles was not explicitly taught, resulting in a lack of a scaffold with which to explain the dissolution. Therefore, it is not surprising that 60% of the students used simple descriptive thinking.

The interviews provide us with the reasons. A minority of students who exhibited this type of reasoning believed that salt dissolving is the spontaneous result of NaCl. They focused on the notion that a solute can exert centralized control, which reflected students' focus on the 'centralized causal process' schema (Talanquer, 2010). Students who used simple descriptive reasoning emphasized the existence of an active entity and believed that there was no interaction. The interviews revealed that major students offered explanations based on simple understanding, without integrating the learned knowledge (within and between disciplines). These students are not taught to integrate related concepts from the perspective of core ideas. Over time, only relevant fragmented knowledge remained accessible to the participants.

To solve this situation, it might be a good approach to unpack topics and connect them to the core ideas (Cooper et al., 2017a). In the existing studies, less attention has been paid to the core ideas of the interactions. Following the framework for analyzing student-generated drawings, this study analyzed student understanding of the interactions. Students who think mechanistically understood the electrostatic interactions. Their drawing in adjacent form showed that the charged ends of the water molecules attract the positive sodium ions and the negative chloride ions. Interactions based on the structure could provide a more accurate explanation of properties. In addition, causal thinking provides a connective structure that facilitates students' comprehension of the dissolution phenomenon, which can play an important role in restructuring students' explanations of real-world problems (Talanquer, 2021). Crosscutting concepts and core ideas need to be integrated into instruction (NRC, 2012).

According to causal relationships, linear causal reasoning, interactive causal reasoning and mechanism reasoning all belong to causal reasoning. The study found only a quarter of students used causal reasoning to explain the task. There is a certain gap between the results of this study and others. According to Moreira et al. (2019a), 40% of the students were able to carry out causal reasoning. The possible reason is they only surveyed the students who come from the 10th grade. The samples of this study are students from grade 9 to grade 12, whose performance varies with grades.

Differences in Five Types of Reasoning among Students by Grade

There were some notable characteristics of the 9th and 11th grades. Linear causal reasoning in grade 9 accounted for almost the same proportion of responses as did simple descriptive reasoning. Compared to linear causal reasoning, there was a high proportion of interactive causal reasoning in grade 11. Grade 12 students exhibited the highest proportion of simple descriptive reasoning, and none exhibited mechanistic reasoning. The last three types of reasoning represent causal reasoning. With increasing grade, students' causal reasoning performance exhibited a declining trend: 46% of 9th graders engaged in causal reasoning, compared with 23%, 16%, and 11% of 10th -12th graders, respectively.

This result is different from the research findings of Weinrich and Talanquer (2016). Their research showed that as the grade increased, the reasoning types of undergraduates became more and more complex. Why do students who have learned numerous concepts exhibit diminished use of causal reasoning and greater use of non-causal reasoning in this study? The following reasons may exist. Firstly, mastering chemical reasoning is seen as a challeng-

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ing task for upper-secondary school students. Talanquer (2021) proposed that reasoning might vary along six major dimensions, named *granularity*, *dimension*, *frame*, *basis*, *mode,* and *focus* in chemistry education. Among them, the *mode* dimension identifies the complexity of causal reasoning, which can provide guidance for answering 'how does this phenomenon occur'. Student performance in this area has been reported to be poor (e.g., Moon et al., 2016; Moreira et al., 2019a; Weinrich & Talanquer, 2016). Secondly, it is also possible that given familiar situations, students tend to simplify the problem, in which circumstances heuristic reasoning plays a greater role (Talanquer, 2018). Interviewed students said they only answered questions based on the knowledge they held and did not engage in in-depth consideration. Consistent with previous research, students tended to use algorithm-based reasoning rather than conceptual reasoning (Nurrenbern & Pickering, 1987). This may be because current education and evaluation emphasize the memory of facts and neglect reasoning (Bao et al., 2009). These reasons may explain why students have rather incomplete reasoning patterns as they progress through grade levels in this study.

The Impact of Reasoning on Understanding Intermolecular Forces and Bonding

There are some studies that link conceptual understanding to reasoning. According to Grotzer (2003), the reason why students have misconceptions is the lack of causal logic. Stains and Talanquer (2007) believed that misconceptions are a kind of reasoning based on 'common sense'. From an inclusive cognitive resource perspective, Taber and García-Franco (2010) proposed the origins of misconceptions reflecting more basic reasoning principles. As the cognitive process that underlies all thinking, causal reasoning plays an important role in conceptual change (Jonassen, 2008). This study explored the relationship between students' causal reasoning and conceptual understanding of the dissolution phenomenon from the perspective of atomic/molecular, which made another exploration in this field. The types of reasoning found in this study can also be used to explain students' misconceptions about 'intermolecular force' and 'bonding' reported in previous studies.

In chemistry, force is an invisible interaction between two submicroscopic entities, represented mainly by bonds or intermolecular forces. These concepts play an important role in understanding dissolution. Misconceptions regarding forces could be an explanation for students' reasoning processes. Students who viewed dissolution as occurring in a single step assumed mechanical reasoning. They thought that when solute bonds were broken, solute-solvent intermolecular forces were formed (Smith & Nakhleh, 2011). Students who thought that dissolution occurs in several steps thought that the first step is to break the bonds of the solute, whereupon the solute disperses in the solvent. The type of reasoning depended on the entities thought to break the bonds and the interaction pattern. For example, some students thought that the interaction between the entities ceased when the ions were separated in the solution. They exhibited fuzzy causal reasoning in which the solute and the solvent were the entities that triggered the breakup, with no interaction pattern.

Reasoning was also reflected in intermolecular forces. For example, the misconception regarding how $MgCl_2$ reacts with H_2O may suggest that attraction between water and ions breaks the covalent bonds in water (Abell & Bretz, 2018). Students who recognize such a process have explained it mechanistically. However, this explanation is unscientific because the force that breaks the covalent bonds in water is not properly understood due to an inadequate understanding of the interactions between atoms/molecules. Some students know that water must play a role, but they could not explain it. Because of their lack of knowledge about the formation of attractive forces during the dissolution process, they used fuzzy causal reasoning. The students were unable to establish relationships between concepts, which hindered reasoning.

The Role of Drawings in Constructing Explanations

Writing, drawing, and speaking are basic and important representational practices. In particular, with the shift from interpretation (learning from representations) to construction (learning with representations), drawing has attracted the attention of researchers (De Andrade et al., 2022; Tang et al., 2019; Tippett, 2016; Tytler et al., 2020). As for the significance of students' involvement in constructing diagrams, Ainsworth and colleagues (2011) proposed five points, including: drawing to enhance engagement, drawing to learn to represent in science, drawing to reason in science, drawing as a learning strategy, and drawing to communicate.

In this study, when students were asked to explain the phenomenon of salt being put into water, they actively negotiated understanding and constructed knowledge. In this process, drawing functioned as a generative rea-

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soning process in that the guiding role of the core ideas is reflected. The findings showed that understanding the electrical nature of the interactions among particles was associated with the construction of reasoning. In the data analysis, the study also found that students had great challenges in drawing. For example, students were able to use arrows to indicate how an entity moves or acts dynamically, which was expressed primarily in linear causal reasoning and interactive causal reasoning. The students who showed linear causal reasoning used one-way arrows to represent the movement of water. In contrast, the students who exhibited interactive causal reasoning used two-way arrows to indicate that the two entities had the same level of activity. Unfortunately, fewer students pointed out the direction of motion between the entities. A majority of students used arrows to indicate the passage of time. While there are some challenges, drawing is still an effective tool to assess conceptual understanding.

Conclusion and Implications

This study demonstrated the presence of five types of reasoning by collecting explanations of salt dissolving from Chinese students aged 15-18. In particular, the proportion of students exhibiting causal reasoning decreased gradually with increasing grades. There was a large correlation between understanding of core ideas and reasoning types. The results suggest that reasoning ability and conceptual understanding of interactions were not at a high level. Few students showed mechanistic reasoning, reflecting the fact that students were not able to flexibly apply causal relationships and disciplinary core ideas to explain a dissolution phenomenon.

Explaining the dissolution phenomenon at the microscopic level allowed students to draw causal inferences to make connections between fragmented concepts and understand the interactions between atoms/molecules. Concepts related to solution chemistry need to be reorganised in students' minds. Through the relationship of structure-properties, when students explain real situational problems, causal reasoning can help with major restructuring. In particular, if students were asked to explain why similar situations have different outcomes (dissolving or not dissolving), this should be effective at generating causal reasoning. Such an approach deserves the attention of teachers.

In terms of course content, using PNM to describe phase changes is part of the chemistry curriculum. However, interactions have received less attention. In fact, based on structure, interactions can offer a more precise explanation of properties. Water solubility, such as that investigated in this study, is a remarkable physical property of salt. The result found that students' understanding of the interaction was relatively poor, which resulted in difficulties in learning concepts (e.g. bonds). Overall, the PNM, especially the atomic/molecular interactions, did not seem to be a useful conceptual tool by which students understood chemical phenomena. Students required additional learning. In teaching, asking about the process is a useful scaffold.

Limitations

There were some limitations. This study focuses on causal reasoning, one of the seven crosscutting concepts. The dissolution phenomenon can also be explained from the perspective of matter and energy, together with systems and system models. In addition, this study only reported the actual performance of Chinese students in causal reasoning and understanding of the core concepts of atoms/molecules interactions under the current chemistry curriculum and instruction. Because this study conducted a survey with a small sample, the results must be interpreted with caution. The study revealed a correlation between reasoning types and the understanding of core ideas. The specific directional relationships need to be explained by a guided instructional intervention, which is the future work.

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Declaration of Interest

The authors declare no competing interest.

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Guanxue Shi	PhD Student, College of Chemistry, Chemical Engineering and Materials Science, Shandong Normal University, Ji'nan, Shandong 250014, China. E-mail: 2020010073@stu.sdnu.edu.cn ORCID: https://orcid.org/0000-0002-1902-5086
Shanshan Lu	Doctor of Education, Associate Professor, College of Chemistry, Chemical Engineering and Materials Science, Shandong Normal University, Ji'nan, Shandong 250014, China. E-mail: 615046@sdnu.edu.cn ORCID: https://orcid.org/0000-0002-5492-6285
Hualin Bi *(Corresponding author)*	Doctor of Education, Professor, College of Chemistry, Chemical Engineering and Materials Science, Shandong Normal University, Ji'nan, Shandong 250014, China. E-mail: bihualin@sdnu.edu.cn ORCID: https://orcid.org/0000-0002-2244-4839