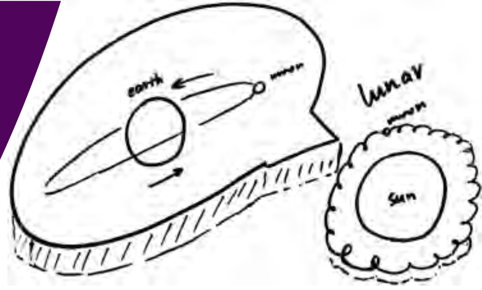
FEATURE ARTICLE

Designing a Coherence- & Concept-Based Modular Course to Facilitate Students' Understanding of Crosscutting Concepts



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Abstract

Crosscutting concepts (CCCs) are superordinate in the scientific concept system, common across disciplines, and very abstract. These characteristics, with the addition of incoherence in their curricular presentation, can challenge instructors. We designed a modular course based on coherence and conceptual understanding. The course structure was arranged in accordance with intra- and inter-unit coherence of CCCs, and each lesson was prepared according to "concept-based instruction" and the "5E instructional model." The results of the pretest and posttest and the semi-structured interviews consistently showed that the participating high school students significantly improved their understanding of CCCs, thus supporting the effectiveness of the modular course.

Key Words: *crosscutting concepts; modular course designing; coherence; conceptual understanding.*

○ Introduction

The K–12 science curriculum standards in many countries have attached great importance to crosscutting concepts (CCCs) and set clear learning requirements for them to deepen students' understanding of science (Gao & Sun, 2019). According to Piaget's cognitive development theory, when students master knowledge of higher levels, it will help them assimilate new knowledge with the same essential characteristics (Feng et al., 2015). CCCs allow students to assimilate disciplinary knowledge, which helps them find the commonality among the seemingly disparate science content. The deep learning occurs during this process of integrating knowledge from different disciplines.

However, the implementation of CCCs encounters some instructional difficulties. Teachers sometimes fail to understand CCCs or to master their instruction, so students do not receive clear guidance in the learning process (NGSS Lead States, 2013). We designed a modular course based on the characteristics of CCCs and aimed to explore an effective way to promote students' understanding. Our project focused on the following questions: (1) What are the key features of the modular course aimed at promoting students' understanding of CCCs? (2) Is the designed modular course effective in improving students' understanding of CCCs?

○ Conceptual Framework

Curriculum design needs to consider the preparations for classroom teaching as well as the setting and adjustment of the curriculum structure (Xu, 2002), and appropriate tools should be used to assess students' performance at the end of the curriculum to detect whether the goal is reached (Tyler, 2014).

Three Characteristics of CCCs

CCCs belong to conceptual knowledge. Conceptual knowledge is an abstract explanation of how the world works (Anderson et al., 2001). Students are able to deeply understand natural phenomena and answer questions related to science if they can master this type of knowledge (Yang et al., 2019). Different concepts are closely related, such that one concept can be used as a prerequisite for understanding another concept (Liu, 2012).

CCCs are more superordinate and abstract than disciplinary concepts, because they are a further generalization of the commonalities among the concepts of various disciplines (National Research Council, 1996, 2012). This process of convergence and simplification makes CCCs dominate disciplinary concepts at a higher level. When adding CCCs into scientific teaching, it is appropriate to reverse the simplified process described above – that is, putting it in a specific disciplinary context and scaffolding learning with concrete facts and materials. Properly selected facts or perceptual, intuitive materials can make students accept and understand abstract concepts more easily (Liu, 2012).

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In addition, CCCs are not constrained by disciplinary boundaries (AAAS, 1989). This may challenge traditional modes of thinking. For example, when discussing something about chemistry, physics, or geography in a biology class, there may seem to be no relationship between these disciplines. In fact, they collectively point to a certain CCC and thus can be further generalized. This kind of integrated learning will increase students' interest and motivation while providing them a bigger picture and deep understanding (Czerniak & Johnson, 2014). Teachers need to guide students in adapting to this process of knowledge construction that weakens disciplinary boundaries.

Concept-Based Strategies Facilitate Understanding of a Particular CCC

Concept-based strategies conform to the students' cognitive development and can provide an understanding-facilitated learning experience by selecting and organizing teaching activities. "Concept-based instruction" is a process driven by concept-oriented questions that help teachers select or design activities efficiently (Yang et al., 2019). Then the selected activities can be organized according to the "5E instructional model," which has proved effective in promoting conceptual understanding (Bybee et al., 2006). For a particular CCC, the combination of these two strategies can address the instructional needs implied by the three characteristics of CCCs discussed above. Thus, abstract conceptual knowledge can be embodied within ordered teaching activities, and the boundaries of disciplines will be broken during the application in various contexts.

Coherence Principle Makes the Learning of Multiple CCCs Orderly

Learning on the basis of prior knowledge can construct a coherent representation of information (Bransford et al., 2000). As an essential factor in students' performance (Schmidt et al., 2005), curriculum coherence should be embodied not only within a unit, but between the units (Fortus & Krajcik, 2012). All the CCCs in the *Next Generation Science Standards* (NGSS) are closely related, and some can be used as the basis for learning others. Therefore, it is necessary to consider the teaching sequence when incorporating all these CCCs in a course, so that students can understand and accept them more smoothly.

Contextualized Open Evaluation Reflects Students' Understanding of CCCs

The learning goal of this modular course was to understand the CCCs. "Understanding" emphasizes the successful migration of concepts. The *National Science Education Standards* document (National Research Council, 1996), predecessor of NGSS, advocates that students have a scientific understanding of the natural world, which requires not only a grasp of the meaning of knowledge, but also the ability to use the knowledge to reason. Thus, examination of the "understanding performance" of the CCCs should be focused on their application in specific situations. Students need to analyze the elements and their relationships in a situation and to make explanations or propose solutions. Therefore, a contextualized open-evaluation method must be used, including interviews, short answers, task reports, concept mapping, problem solving, and so on (Zhang & Liu, 2010).

○ Design of Modular Course

The structure of our CCC modular course was set according to the coherence principle, and then combined with the "concept-based instruction" and "5E instructional model" to prepare each lesson.

Set the Course Structure

The CCCs learned first should serve as the basis for the CCCs learned later, and the units learned first should pave the way for subsequent units. Thus, the course was structured in the three phases outlined below.

Determine All the CCCs to Be Taught

We chose the CCCs in NGSS as teaching content, because NGSS has synthesized and complemented the unifying concepts or common themes described in previous science curriculum documents. And of the four grade groups divided in NGSS, the CCCs in grades 9–12 were selected by our project because of their larger number and more comprehensive interpretation. We merged the concepts that highly overlapped, and supplemented some concepts in consideration of coherence. For example, the definition of the scale was added. Finally, a total of 21 CCCs were chosen to be taught in the modular course.

Divide the CCCs into Different Units

The seven crosscutting themes in NGSS are closely related, and more than one theme can be embodied simultaneously in the same phenomenon or situation. For this reason, the 21 CCCs were divided into three units. *System* is widely used as a kind of investigation and research unit to explain the nature of science (National Research Council, 1996), and constructing system models is also an effective means of science learning (Baumfalk et al., 2019). Thus, the theme "System" served as the first unit to provide a basis for understanding other CCCs. The second unit, "Scale and Proportion," was aimed at helping students understand the systematized phenomena or processes in nature from a quantitative perspective. With the foundation of the first two units, students could focus on the transfer of matter and energy systematically and quantitatively in the third unit, "Energy and Matter." The CCCs in each unit were sequenced coherently.

Allocate Periods to Each Unit

Of the 13 lessons (one hour per lesson) offered by the partner high school, two lessons were used for the pretest and posttest; the remaining 11 lessons were allocated according to the number of CCCs to be learned in each unit. Considering that the theme "Energy and Matter" had been taught as disciplinary core ideas in middle school, only two periods were allocated to CCCs under this theme. The final course-structure framework is shown in Figure 1.

Prepare the Lessons

In order to encourage students to actively construct an understanding of CCCs, all the teaching activities in each lesson were selected and organized according to "concept-based instruction" and "5E instructional model." Here, take lesson 3 of the unit "System" as an example to demonstrate the three-step design process.

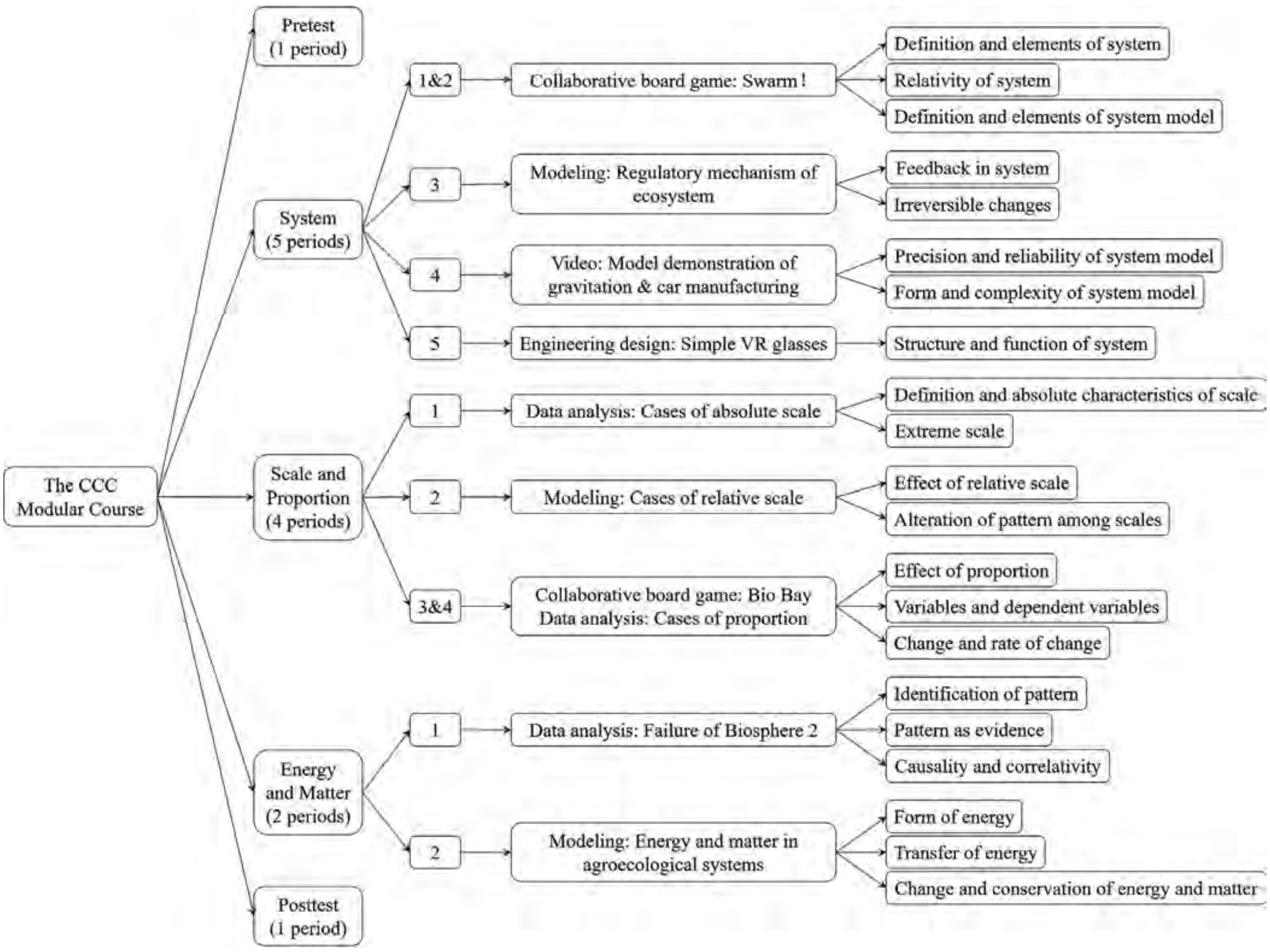

Figure 1. The structural framework of the CCC modular course.

List the CCCs in a Lesson

Students need to understand that (1) feedback (negative or positive) can stabilize or destabilize a system and (2) some system changes are irreversible.

Propose Questions & Sequence Them

The questions in the CCCs were proposed and ordered according to the logic of student cognitive development: (1) What is negative (positive) feedback? (2) What changes will happen to a system under negative (positive) feedback control? (3) Are the changes in the system reversible? These concept-oriented questions can stimulate teachers' thinking and drive them to collect and organize teaching resources in the next step (Yang et al., 2019).

Select & Organize Activities

The activities in this lesson revolved around building system models, and specific information is listed in Table 1.

○ Implementation

The modular course was implemented twice in the same high school in the form of a school-based elective course, each lasting one semester. This school is one of the first-class public high schools nationally. The purpose of the first implementation was to modify the course and teaching, while the second implementation was to assess the effectiveness formally. We used the action research method to analyze the effectiveness of the course through comparing students' understanding of CCCs before and after course implementation.

Subjects

A total of 38 students from 11 different classes participated in the second course implementation, including 18 boys and 20 girls. All the students were at senior grade 1 and were taking the course for the first time. The average attendance rate of the course was 95.7%. Having collected 36 valid pretest papers and 36 valid posttest papers, 34 groups could be validly matched. In addition, nine student volunteers participated in focus-group interviews, including five boys and four girls.

Tools

The interval between the pretest and posttest was more than three months. The items in the two tests were identical: there were four context-based short-answer questions, including 13 subquestions

Table 1. Selected and ordered activities in the lesson 3 of the unit "System," based on the "5 Es": engagement, exploration, explanation, elaboration, and evaluation.

Sequence	Teaching Activities
Engagement	Students briefly discuss a common scenario related to the urination reflex, which is an example of positive feedback. This mini-activity is designed to attract students' attention, and the discussion may expose their misconceptions.
Exploration	Students construct system models to describe the process of "soil erosion" (an example of positive feedback) and "stable predation relationship between wolves and rabbits" (an example of negative feedback), respectively. Then discuss: (1) What is the difference between the interactions of these two systems? (2) What changes happened to these two systems because of the different interactions? (3) Are the changes occurring in the two systems reversible? This part is to help students construct understandings of feedback and irreversibility through their own thinking.
Explanation	Students modify their own models, referring to the sharing by other groups and the teacher's demonstration. If students encounter difficulties in answering question 1, the teacher can guide them to think in this direction: If event A causes event B, then how will B affect A in turn? After students have expressed answers in their own language, the teacher summarizes these and demonstrates the specific formulation of the two CCCs. Students check the idea gained in exploration with the demonstration to reinforce their understanding.
Elaboration	After exploring in the context of biology, students apply their understanding to two new situations: (1) a thermal control circuit in physics and (2) gas explosion in chemistry. They need to construct system models to describe the two systems, and judge the type of feedback and whether the changes that occur in these systems are reversible. The purpose of this activity is to allow students to understand that feedback and reversibility are common concepts among disciplines and to break the boundaries.
Evaluation	Two questions are used to evaluate students' understanding: (1) Referring to a scenario mentioned at the beginning of class, why does a person's desire to urinate become stronger if he or she cannot get to the toilet quickly? (2) Are there other examples of positive (negative) feedback? Are the changes in these systems reversible?

that cover the 21 CCCs in the course. A short-answer question is shown in the Appendix as an example. Two raters independently scored the students' test papers, and results of the rater consistency reliability analysis showed that the kappa values of all the CCC scores were >0.76, indicating that the two raters had high consistency. After discussing and reaching agreement on the controversial scores, the results of the scoring were further analyzed as quantitative data, and the students' responses on the test paper were used as qualitative data.

We conducted seven semi-structured group interviews with nine students. The students were interviewed after the pretest, after the posttest, and after every two or three lessons, for an average duration of 40 minutes. The two interviews conducted after the pretest and posttest revolved around student understanding of the questions in the test paper, and the remaining five interviews focused on the impact of classroom teaching activities on students' understanding of CCCs. The data obtained through interviews can detail students' thinking process and helped us detect the changes in their understanding. In addition, we collected the classroom recordings of each lesson and the student products as qualitative data in our analysis of the effectiveness of the CCC modular course.

○ Data & Analysis

Our project combined quantitative and qualitative analysis, on the one hand to reflect the changes in students' understanding of CCCs after the course, and on the other hand to analyze the impacts of coherence principle- and concept-based strategies used in course design on students' learning of CCCs.

Changes in Students' Understanding of CCCs

The maximum score of the test paper is 47. In the quantitative analysis, the t-test of the 34 valid paired samples showed that there was a significant difference ($P < 0.05$) between the students' pretest (18.00 ± 4.41) and posttest (28.56 ± 6.63) understanding. The overall assessment scores are presented in Figure 2. Specific to each CCC, the scoring rates of in the pretest and posttest are shown in Figure 3. A Wilcoxon test was performed to compare the distribution of the scores in pretest and posttest of each CCC, and the CCCs with significant difference ($P < 0.05$) are marked with asterisks in Figure 3. The quantitative results indicated that students' understanding of most CCCs had significantly improved as a result of the course. Specifically, students' understanding of 15 CCCs was improved significantly, while that of six CCCs was not changed.

The results of the interviews were consistent with the quantitative analysis. For the 15 CCCs with significant differences, students' understanding of them in the posttest interview was better than that in the pretest. In the pretest interview, we can obviously observe some vague or wrong understanding in students' expressions. For example, some students showed a vague understanding of the positive feedback in the process of forest fire expansion. A student said in the interview:

> *"The effect of the conditions should be there all the time . . . the local area was experiencing the extremely hot weather, I think the effect*

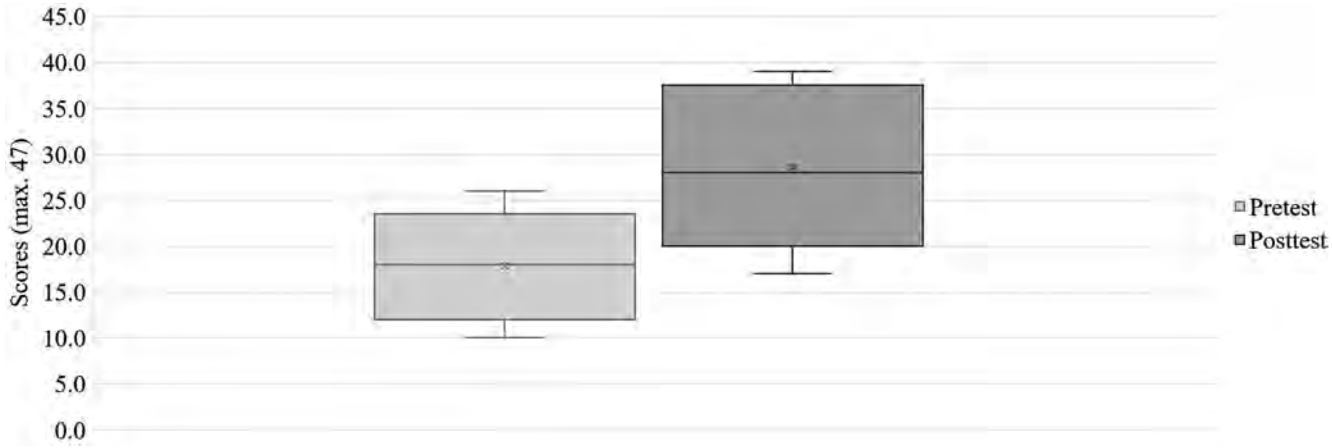

Figure 2. The overall assessment scores of CCCs in pretest and posttest.

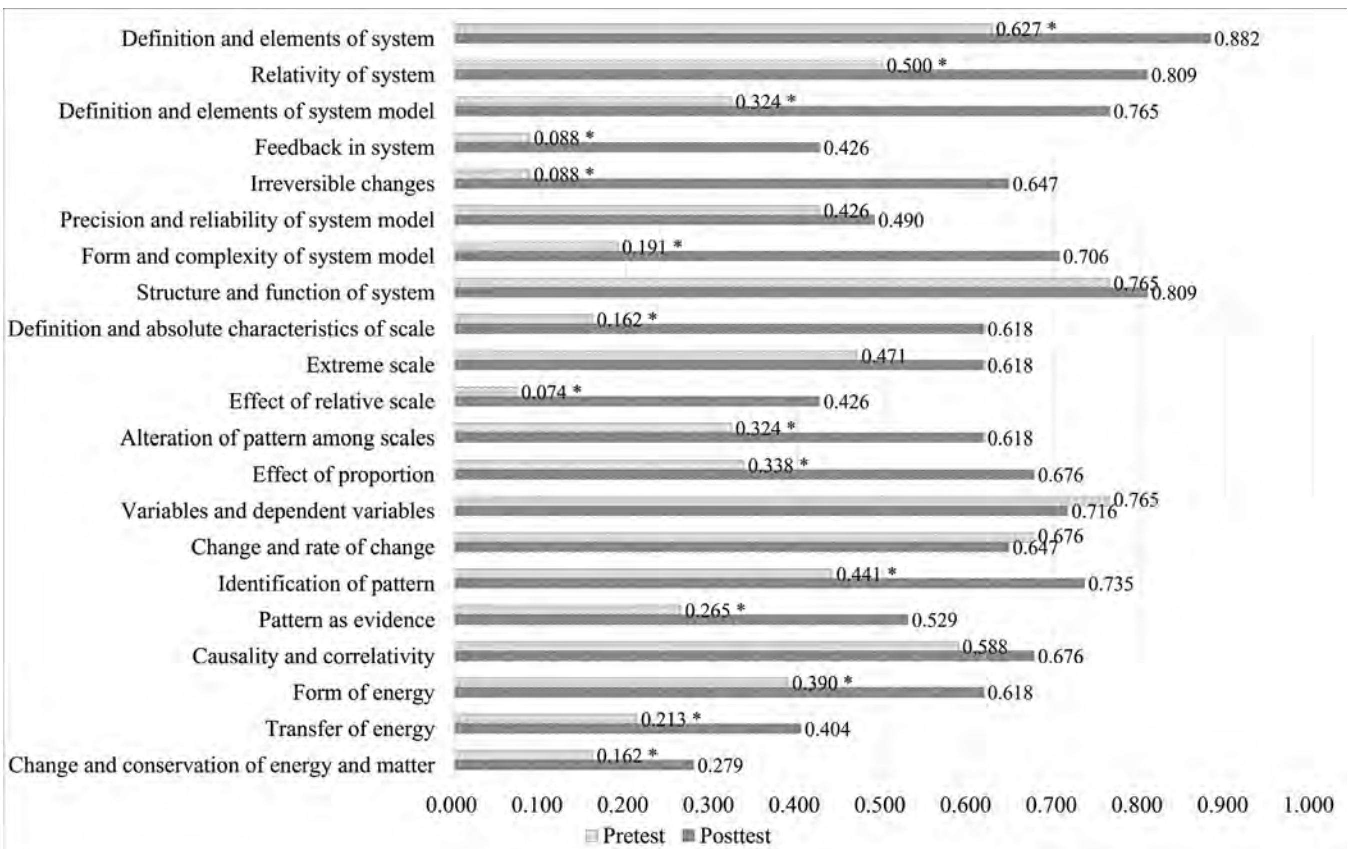

Figure 3. The scoring rate of 21 CCCs in pretest and posttest.

of it was not one-off, but run through all this process. The same as the hot weather, I think the abundant forest was also a persistent factor that ran through the entire fire expansion." – Zhao

The student was partly aware of the mutually reinforcing effects between the forest fire and high temperature or combustibles, but he couldn't explain or express the positive feedback clearly. In the posttest interview, by contrast, students could express a better understanding of feedback, as this student did:

"The high temperature and hot air aggravated the fire, and the fire aggravated these two factors in turn." – Dai

Take the concept of "scale" as another example. Students possessed misconceptions in the pretest interview, as seen in this comment:

"I think the scale is a range. The spatial scale refers to the range covered by the space. That is, it has a specific size." – Niu

In the posttest interview, students expressed their improved understanding as in the following example:

"Before the course I didn't know what it was, but now I know it was a kind of unit." – Wang

As for those six unchanged CCCs, the analysis of the interviews showed that, excepting "the precision and reliability of system models," students had a certain understanding of the other five CCCs before the course. That may be why the results were not significantly different for these. Take "Extreme scale" as an example:

> *"My middle school physics teacher taught us a method called transformation. For example, sound is produced by vibration. If the vibration of the drum surface is hard to observe, we can tear a paper into pieces and sprinkle it on the drum. Then we can see the pieces shaking. This is the transformation method, that we can seek some ways to magnify the small, or something like that."* – Shan

The student had gained some understanding of extreme scales from the previous learning experiences, so she could judge that the systems that are too small, too large, too fast, or too slow need studying indirectly.

The CCC modular course failed to improve the students' understanding of "the precision and reliability of system models." The possible reason we found in the posttest interview was that the terms ***reliability*** and ***precision*** were too abstract and difficult for students to understand.

Impacts of Coherence Principle & Concept-Based Strategies on Students' Learning of CCCs

The structure of the modular course was set according to the principle of coherence: that is, the CCCs within and between units were coherent. Students' expression in interviews supported the positive effect of coherence in promoting their understanding of a CCC. For example:

> *"I didn't know much about the alteration of patterns among scales, because I didn't have a comprehensive understanding to the scale before that. That is, the concept we discussed now, it is based on 'scale.'"* – Dai

In classroom teaching, the engagement activities were used to attract students to think in the direction preset by the teacher. Take the mini-activity of the lesson "Definition and elements of system" as an example:

> *"Teacher: Is the cell a system?*
> *Student A: Yes!*
> *Student B: No.*
> *Student C: It is possible.*
> *Student D: That depends on how to define the system."*

In this way, students would be focused on how to define a system and then smoothly enter the exploration part. As for activities in exploration and explanation, we found them effective in helping students construct understandings of CCCs. Taking the activity in the lesson "Relative scale" as an example, students need to analyze the relationship between the symptoms of multiple diseases and the molecular pathogenic mechanisms of various toxins, and match them one by one.

> *"I did use this thinking process in the activity, that is relating different scales. I connected the chemical nature with the symptoms it could cause, and then I felt that I got this thinking process imperceptibly. And finally I checked the concept you demonstrate, this helped me express the thinking process in my mind more clearly."* – He

The student successfully constructed the understanding of relative scale through the experience of exploration, and further clarified the formulation of it during the explanation and deepened her understanding.

The activities in elaboration prompted students to break the disciplinary boundaries. Take the activity in the lesson "Definition and absolute characteristics of scale," for example:

> *"At first, I think scale was a kind of unit in physics, such as meter. And now I find that scale has a broader meaning, because it can also explain things related to biology."* – Zhao

The student extended his understanding of scale from one disciplinary context to another, thus helping him understand the commonality across the disciplines.

○ Conclusions & Discussion

The key features of the CCC modular course are its coherent course structure and concept-based classroom teaching, and the findings of our project supported the course's effectiveness in improving students' understanding of CCCs. These conclusions indicate that applying the concept-based strategies to instruction of a particular CCC, and the coherence principle to arrangement of multiple CCCs, can be an effective way to teach.

The CCC modular course's structure was set according to inter- and intra-unit coherence, and classroom teaching was designed through a three-step approach that combined concept-based teaching and the 5E instructional model. These designed results can serve as a practical reference for science teachers to prepare their CCC instructional plan. For example, some CCCs can be learned first to pave the way for others. In addition, our project provides two types of information for professional development on CCCs. One is students' understanding of CCCs, including correct, ambiguous, and incorrect information. The other is the effective teaching approach for CCCs based on coherence and conceptual understanding. This information can be used to help teachers master the instruction of CCCs.

Most CCCs in our modular course were taught only once because of the limited number of class periods. The impact of the course may be increased if there is more time for teaching. The data reported here were collected from a small sample, and the effectiveness of the course for more types of students remains to be tested. Specialist teachers may encounter difficulties in designing or using this CCC course, which includes activities drawing on various disciplines and contexts, necessitating cooperation between different disciplines in preparing lessons.

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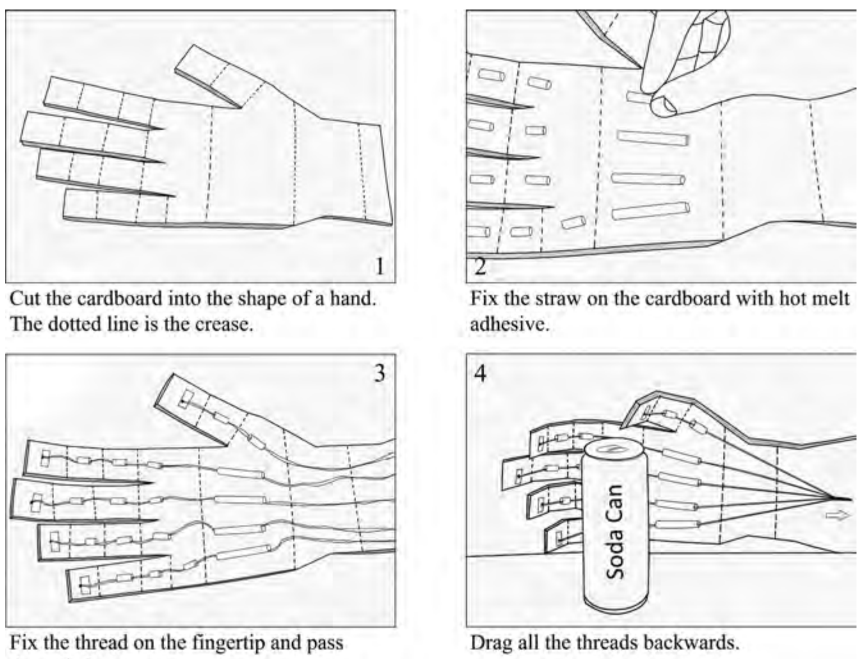
Appendix

An example of the short-answer questions in pretest and posttest

"Biomimetic machines" have been a popular topic in recent years. These are machines that possess concentrated functions, high efficiency, and biological characteristics that imitate the form, structure, and working mechanism of organisms. Ming made a simple manipulator model using common materials and finally successfully grabbed an empty soda can. The materials include cardboard, straws, hot melt adhesive, thread, and scissors. The process is shown in the figure below.



Q1. Please evaluate the advantages and disadvantages of this model in the function of grasping.

Q2. Propose a brief improvement plan for one disadvantage identified in your response to Q1.

Q3. Some mechanical arms used by people with disabilities are heavy. If you were research staff in a factory manufacturing these, what would you do to address this fault? What is the spatial scale that your resulting improvement will be measured on?