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Students' Understanding of Cells & Heredity: Patterns of Understanding in the Context of a Curriculum Implementation in Fifth & Seventh Grades

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ABSTRACT

This study explores upper-elementary and early-middle-school students' ideas about cells and inheritance and describes patterns of understanding for these topics. Data came from students' responses to embedded assessments included in a technology-enhanced curriculum designed to help students learn about cells and heredity. Our findings suggest that the instruction aided students in progressing to more sophisticated levels of understanding, especially by reviewing non-normative ideas and integrating new content into their previous understandings. Students, however, tended to struggle in distinguishing genes, chromosomes, and DNA and had some difficulties connecting the cell division process with the inheritance of genetic material.

Key Words: Genetics; heredity; student learning; middle school science; patterns of understanding; biology inheritance.

Understanding genetics can help students comprehend important issues in society such as genetic testing for diseases (Lewis & Wood-Robinson, 2000; Ayuso & Banet, 2002; Dougherty et al., 2011) and genetically modified foods (Venville et al., 2005). Thus, there is a need for students to learn about cells and inheritance because these topics are important for developing students' scientific literacy as it relates to genetics (American Association for the Advancement of Science, 1993; Tsui & Treagust, 2007; Shaw et al., 2008; National Research Council, 2012).

Research on secondary students' understanding of genetics and heredity shows that these topics are difficult for students to learn because they are complex and abstract (e.g., Stewart, 1982; Clough & Wood-Robinson, 1985; Moll & Allen, 1987; Bahar et al., 1999; Lewis & Wood-Robinson, 2000; Duncan & Reiser, 2007; Tsui & Treagust, 2007; Duncan et al., 2009). Moreover, many students have problems understanding genetic phenomena characterized by different levels of biological organization, for example, in connecting how the interactions of genes and proteins at

the molecular level affect organismal expression of traits (Duncan & Reiser, 2007). Students tend to understand important genetic-based concepts and processes in a fragmented way – for example, inconsistently explaining the characteristics of genetic information for different types of cells within the same individual (Chattopadhyay, 2005).

Research has also identified non-normative ideas students have that are related to genetics. For example, secondary students often (1) believe that a dominant allele is stronger, bigger, or more beneficial than a recessive allele (Ayuso & Banet, 2002); and/or (2) conflate the concepts of genes, alleles, and chromosomes (Banet & Ayuso, 2000; Lewis & Wood-Robinson, 2000; Wood-Robinson et al., 2000; Shaw et al., 2008; Quinn et al., 2009).

Moreover, studies conducted with younger students, between 4 and 12 years old, show examples of non-normative understanding of heredity, including ideas such as that mothers contribute more traits to the offspring than fathers (Clough & Wood-Robinson, 1985; Springer, 1996; Terwogt et al., 2003) and that trait inheritance is

based on the sex of parents and child instead of being equally passed down from both parents (Kargbo et al., 1980).

Because most research on students' understanding of genetics has focused on the secondary level, there is a paucity of research on inheritance for 10- to 12-year-old students that describes and tracks students' patterns of understanding (Venville et al., 2005). In addition, Duncan et al. (2009) emphasized the importance of conducting more research on students' thinking and learning at late elementary and middle school levels to support better instruction at the secondary levels. Moreover, it

is important to determine how students learn in the context of curriculum implementations that serve as the foundation for students' understanding of complex genetics concepts at the secondary and college levels.

The National Research Council (NRC, 2012) has developed *A Framework for K–12 Science Education: Practices, Crosscutting Concepts,*

Understanding genetics can help students comprehend important issues in society such as genetic testing for diseases and genetically modified foods.

and Core Ideas that describes content and practices for different grade bands as a first step toward the development of new science standards. Within the framework, “Heredity: Inheritance and Variation of Traits” is the third core idea of the life-science disciplinary area. Although the framework is an important first step toward describing what students should learn about heredity and its related concepts by the end of each grade band, it is unclear how students’ conceptions develop across these grade spans. Therefore, the purposes of the present study are to explore upper-elementary and early-middle-school students’ ideas about cells, reproduction, and inheritance and to describe suggestive patterns of understanding for these topics over time, through the implementation of a technology-enhanced curriculum designed to develop coherent understandings of complex science.

○ Curriculum Implementation & Research Methods

Instructional Units

Teachers implemented instructional units developed in the Web-based Inquiry Science Environment (WISE) – a technology-enhanced learning environment that scaffolds inquiry with a navigation system, enables students to solve real-world problems, and emphasizes reflection on the learning process (Linn & Slotta, 2000; Kali et al., 2008). The 8-week-long fifth-grade unit focused on helping students to distinguish between inherited and acquired traits in organisms, as well as trait variations. Students also learned about reproduction through plants, to help them make connections between reproduction and traits and between the characteristics of plant and animal cells. Complementarily, students learned that cells are building blocks of all living things and were introduced to unicellular and multicellular organisms.

The 5-week-long seventh-grade unit builds on what students learned in fifth grade by deepening their understanding of cells, reproduction, and inheritance, including characteristics of plant and animal cells, plant and animal reproduction, and the mechanisms of inheritance. Students learned about cell molecules, structures, and functions related to inheritance – DNA, alleles, genes, and chromosomes, as well as the relationships among these concepts. Students focused on the Mendelian mechanisms of genes’ inheritance and connected what they learned about cells’ genetic material to mitosis and meiosis (Williams et al., 2012). Details of the content covered in each activity are described in Table 1.

Both WISE units included a set of online embedded assessments whose purpose was to capture students’ progress in learning the particular content of each activity, as well as to connect the material with students’ personal experiences or with the content of previous activities, so that students could integrate their ideas into more sophisticated levels of understanding. Moreover, these assessments provided the opportunity to track student progress during instruction and to provide information to teachers for the purpose of informing instruction. The embedded assessments encompassed a variety of tasks, including explaining concepts, analyzing data, solving problems, and using simulations (see Figure 1).

Data Sources & Analysis

This cross-sectional and qualitative study (see Miller, 2007) was conducted in a socially and economically diverse, Midwestern,

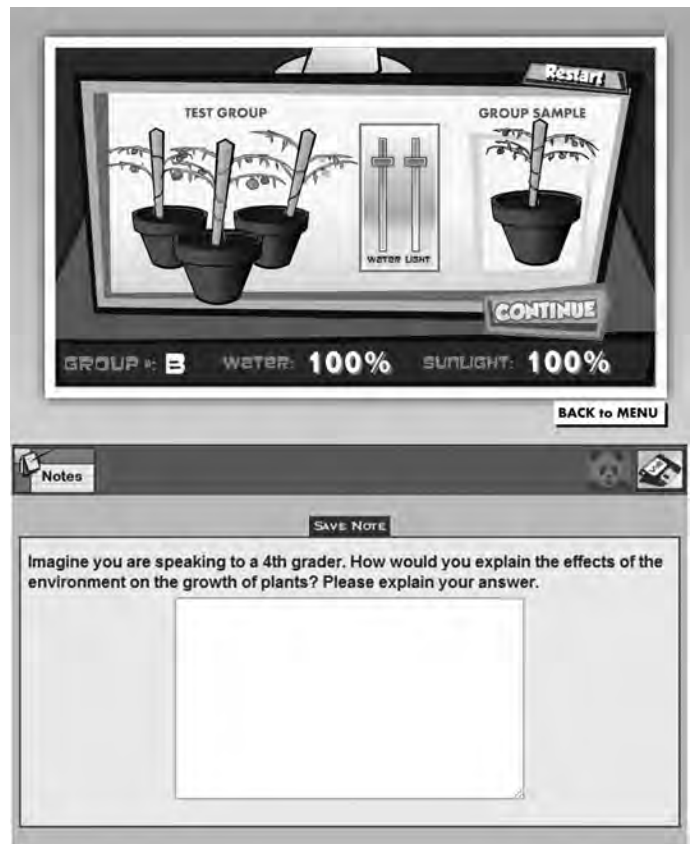


Figure 1. Example of the correspondence between one simulation activity designed to observe the effects of environmental factors on plant growth and its respective embedded assessment.

suburban school district. Four teachers from two upper-elementary schools implemented the fifth-grade technology-enhanced curriculum, and two science teachers from the middle school implemented the seventh-grade unit. The data source for the study was responses to online embedded assessments included and collected in the fifth- and seventh-grade units that were used during the instructional units. We selected a sample of 90 fifth-graders and 54 seventh-graders who worked with the units in the 2010–2011 school year. The criterion for selecting the sample considered students who completed all the embedded assessments included in the analysis, for their respective grade-level units. Fifth-grade students composed a larger student sample because teachers highly encouraged students to complete all the embedded assessments along the unit.

Eleven fifth-grade and nine seventh-grade embedded assessments that referred to topics of cells, reproduction, and inheritance were selected for the data analysis that was completed using an open-coding procedure (Bohm, 2004). For each embedded assessment, students’ responses were broken down into multiple categories. Preliminary categories of students’ ideas were reviewed and analyzed according to the context of the WISE units (e.g., sequence of activities, type of activities), knowledge of the discipline, and researchers’ background knowledge (e.g., previous implementations). Careful analysis of different types of students’ responses provided further

Table 1. Summary of activities in the WISE grade heredity units.

Fifth-Grade Unit	Seventh-Grade Unit
<p>1. Where Do Our Different Traits Come From? Introduction to the biological inheritance unit and the driving question, "Why do organisms have similar and different features?"</p>	<p>1. Will You Help Us Solve a Mystery? Introduction to the unit and its driving question, "Who is the parent?"</p>
<p>2. Similarities and Differences among Organisms. Introduction to inherited and acquired traits of animals, and trait variations. Students explore traits' similarities and differences among themselves and review examples of how traits can be influenced by the environment.</p>	<p>2. Inherited and Acquired Traits. Introduction to the study of "traits." Students distinguish between inherited and acquired traits of plants and animals.</p>
<p>3. Plant Traits. Investigation of inherited and acquired traits of plants by observing short and tall Fast Plants. This example of plant variation can help students observe phenotypic characteristics.</p>	<p>3. The Mechanism of Sexual Reproduction. Introduction to the concept of sexual reproduction. Students learn about DNA, alleles, genes, and chromosomes, as well as the relationships between these entities. Punnett squares are used to determine genotypes and phenotypes of parents.</p>
<p>4. Audrey's Garden. Inquiry investigation and introduction to Audrey's Garden gaming environment. Students interact with a virtual garden to understand how environmental factors can influence plant traits.</p>	<p>4. Looking More Closely at Sexual Reproduction. Review of the process of plant reproduction, especially in relationship to DNA and traits. Students learn about the process and function of meiosis and apply these ideas to explaining how traits are passed from parent to offspring.</p>
<p>5. Cell Growth and Reproduction. Investigation of cell structure and plant reproduction. Students learn similarities and differences between plant and animal cells and learn about plant reproduction. Students connect these experiences to their Fast Plant investigations.</p>	<p>5. Sexual and Asexual Reproduction. Comparison between sexual and asexual reproduction. Students use the ideas learned in previous activities to build their explanations.</p>
<p>6. Traits for Survival. Investigation of how traits evolve over time as a result of organisms interacting with the environment.</p>	<p>6. Plant and Animal Cells. Introduction to the ideas of cells as building blocks and that all living things are made up of cells. Students explore plant and animal cell visualizations and learn about multicellular and single-celled organisms. They also interact with visualizations of mitosis.</p>
<p>7. Solving Audrey's and Fast Plant Dilemma. Application of concepts to determine whether plant traits, including both Fast Plants and Audrey's tomato plants, are inherited or acquired. Students also respond to the unit's driving question.</p>	<p>7. Solving the Mystery. Application of concepts to determine genotypes and phenotypes of plants in first and second generations. Students also respond to the unit's driving question.</p>

insights into how students were making connections among science ideas, and the iterative analysis of student responses resulted in categories of student understanding (see example in Table 2). To illustrate the general trends observed in students' responses, frequencies per each category were recorded. On the basis of our analysis and for organizing the findings' presentation, embedded assessments were classified into two groups: *cells and reproduction* and *traits and inheritance*.

Categories of students' ideas were used to identify patterns of understanding according to the knowledge integration (KI) framework, which defines student learning as the continuous addition of new ideas and the resulting reorganization of their personal knowledge (Linn, 2006). The framework captures the ways in which students use new concepts to describe and connect scientific

normative ideas to explain phenomena or solve problems (Linn & Hsi, 2000). In the present study, students were considered to progress in their understanding when they provided explanations with more sophisticated levels of understanding and connected normative ideas about cells, reproduction, traits, and inheritance. For example, previous research indicates that students tend to explain concepts of cell division and trait inheritance as separate events without making detailed connections (Moll & Allen, 1987). Thus, students are able to make progress in their understanding of heredity when they establish adequate relationships between alleles, genetic material, and meiosis. Successive comparisons of students' responses in fifth and seventh grades, within the context of both units, made it possible to explain students' patterns of understanding.

Table 2. Categories of responses created for a fifth-grade embedded assessment.

Embedded Assessment: Do children get traits from both parents? Explain your answer.	
Category of Students' Ideas	Example
Explanations focus on traits inherited from both parents.	Yes because you can have like the color of your mom's hair but you can have the color [sic] of your dads eyes.
Explanations focus on genes' inheritance from both parents.	Yes, because you get DNA from your mother and father through sperm (father) and an egg (mother).
Explanations focus on family traits (instead of the parents).	It all depends but I would say no because you can get traits from your grandpa or grandma or aunt so you can get traits from anyone in your family!!!
Explanations focus on traits inherited from only one parent.	No, I think they only get [traits] from your mom who you are born from.
Recognize that both parents give traits without further explanation.	Because when the parents make the baby it takes both so it gets traits from both of each other.
Other explanations.	It sort of dependents because say if you [sic] are the oldest and the youngest I believe you get most of your mom's looks but if you are the middle child you kind of don't look like your parents.

○ Results

Students' Performance on Embedded Assessments

In this section, evidence of fifth- and seventh-grade students' performance on the embedded assessments is provided. For each grade level, findings of students' performance are organized according to the content groups: *cells and reproduction* and *traits and inheritance*.

Fifth Grade

Concerning *cells and reproduction*, 66% of fifth-graders recognized that both plant and animal cells have similar components such as the nucleus, cytoplasm, and the vacuole, whereas few students focused their responses on size, needs, and appearance. Regarding differences, 72% of the students correctly identified the cell components particular to plant cells (i.e., cell wall, chloroplast, and large-sized vacuole).

Students had varied explanations of why plants and animals are multicellular organisms. Twenty-seven percent indicated that both plants and animals are multicellular because each cell has specific functions to perform, while 13% indicated that the combination of different cells helped the organism achieve its integrated functioning. Another 13% explained that animals and plants are multicellular because they are composed of specific parts and, accordingly, each part is composed of specific types of cells, and 9% focused on the small size of cells and the reproduction process – by indicating that organisms had to be organized in cells to create a new offspring. Similar responses were mentioned in another embedded assessment that prompted students to explain the differences between red blood cells and muscle cells, although the functional argument was more frequent.

Concerning *traits and inheritance*, most fifth-graders (73%) recognized that both parents contribute to the traits of an offspring, for example, by recognizing that in the Audrey's Garden activity traits are passed down from the parent plants. However, they once again differed in their explanations. Most commonly, students provided

examples of each parent's traits to argue that children had characteristics of both parents (46%), or they mentioned "family traits" without mentioning the parents (21%). Although students were taught that genes are the basic units of inheritance, only 6% articulated that heredity implied the transmission of genes from parents to the offspring, which implies that despite learning about genes in the unit, students rarely invoked them when discussing inheritance.

As they progressed through the unit, students adequately characterized and distinguished acquired and inherited traits in plants and animals. At the beginning, students provided examples of both types of traits without describing the conceptual difference. By the end of the unit, student responses showed that most students were able to explain this difference with higher levels of integration (see Table 3). In general, students correctly recognized that traits can be classified as *inherited*, which means that those traits were passed down from the parents, or *acquired*, which means they were affected by environmental influence.

Seventh Grade

Concerning *cells and reproduction*, results demonstrated that students were able to provide more detailed explanations for the characteristics of plant and animal cells. The typical student response was that "the plant cells are rectangular and have a cell wall and are filled with chloroplasts and chlorophyll, while the animal cell is rounded and has no cell wall and no chloroplasts," which is evidence that students compared cells on the basis of their components and shape. However, students had difficulty explaining the presence of genetic material in cells. Students tended to ignore chromosomes and genes when they explained the structural and functional features of cells and only did so when explicitly asked, such as in the embedded assessment about differences between the parent cell and the daughter cells in meiosis. In that assessment, most students correctly responded that daughter cells receive only half of the parent cell's chromosomes or genetic material, so offspring created through sexual reproduction had a mix of parental genetic materials. Similarly, other embedded assessments

Table 3. Examples of students' progress during the fifth-grade unit: distinguishing inherited and acquired traits.

Embedded Assessment	Basic Explanation	More Integrated Explanation
1. Imagine you are speaking to a fourth-grader. Provide an example of what you think are (1) inherited traits and (2) acquired traits in animals.	Inherited traits are from your family, and acquired traits are like pierced ears.	An inherited trait is a trait you get from your parents, like the color of your eyes. An acquired trait is something you get from the environment, like a tattoo or a scar.
2. John and his mother have blue eyes. His brother, sister, and father all have brown eyes. John is often told that he "has his mother's eyes." How can this trait be characterized?	Inherited, because he and his mom both has [sic] blue eyes, he must have inherited [sic] this trait from his mom.	Inherited, because he got those blue eyes from his mom because the blue took over the brown.

- Chromosomes in the nucleus are made up of DNA, and genes are part of DNA. The chemicals that are in DNA dictate how the genes of an organism will affect its appearance.
- DNA is the chemical that makes up genes, and genes stick together to form chromosomes.
- Chromosomes make genes, and genes make up DNA.

Figure 2. Examples of seventh-grade students' responses to the embedded assessment about the relationship among chromosomes, DNA, and genes, with different levels of accuracy.

also showed that students recognized meiosis as a mechanism of cell division, but they rarely mentioned that a consequence of this process is that traits are passed down from parents to offspring.

In addition, seventh-graders demonstrated some understanding of the difference between sexual and asexual reproduction. Fifty-three percent of the students, however, emphasized the number of parents required in each type of reproduction rather than the characteristics of the daughter cells' genetic material. Not surprisingly, this is connected with the fact that one third of the students recognized the implications of sexual and asexual reproduction for genetic diversity, ease of adaptation, and number of descendants. Regarding *traits and inheritance*, responses showed that many students could accurately differentiate the concept of phenotype and genotype and were able to explain how the organism's genes and alleles are related to its genotype by providing good examples of that difference. Students tended to describe genotype as "combination of alleles" or "genes that choose traits" and phenotype as the "expression of the genotype." Most students (59%) were able to explain the difference between a dominant and a recessive trait and how these alleles interact to express specific phenotypes. However, a group of students (31%) maintained the non-normative idea that dominant alleles referred to stronger, better, or bigger traits. The unit activities and their respective embedded assessments show that students were able to use their knowledge to solve problems related to mechanisms of inheritance. For example, 70% of the students predicted

and described correctly the F_1 and F_2 offspring phenotypes when crossing a homozygous dominant plant with a homozygous recessive plant. In general, students explained that recessive traits were not expressed but masked in the first generation and that therefore they can be passed down to the next generation with a certain probability. Although the instructional activities introduced and worked with the Punnett square, only 11% of students' responses provided evidence that they were using this procedure to predict the F_2 offspring accurately.

Despite students' improved understanding of cells, traits, and inheritance, many continued to struggle with identifying the relationships among chromosomes, DNA, and genes. More than one-

third of the students differed in their explanations for each concept, in some cases including non-normative ideas or using the concepts interchangeably. For example, Figure 2 shows how some students struggled to locate, describe, and analyze these relationships.

Progressions in Student Responses in Grades 5 & 7

Because students' understanding of topics in seventh grade are connected to what they learned in fifth grade, we analyzed a common embedded assessment for both grades to provide further evidence of how students were reframing their ideas when they added new content to their existing knowledge. This assessment item, administered at the middle of both units, asked students to explain whether it is true that girls inherit most of their features from their mothers (or boys from their fathers). Table 4 shows that students in fifth grade used more varied explanations to respond to the embedded assessment. A group of students (13%) considered this statement to be true, and their arguments were based on the common traits that they shared with their own parent of the same sex. Other students responded that the statement was false, and their explanations consisted of giving examples of traits they shared with their parent of the opposite sex (32%) or simply paraphrasing the question statement (44%). Because the seventh-grade unit introduced new topics of cell division and trait inheritance at the cellular level, students at this grade level tended to respond correctly (84%), providing more sophisticated and detailed explanations. In some cases, students

Table 4. Examples of student responses in fifth and seventh grades in a cross-grade embedded assessment.

Embedded Assessment: Is it true or false that boys inherit more traits from their fathers than from their mothers? Please explain your answer.	
Fifth-Grade Students	Seventh-Grade Students
True, because guys are taught everything by their dads like sports and stuff like that.	It is false. All offspring [sic] inherit half of their chromosomes from their mother and half from their father, so there is an equal chance for boys to inherit more from their mother than from their parent.
I look like both of my parents but I think I look more like my dad than my mom. My face structure is more like my dad's but my eyes look more like my mom's eyes.	False both parents put in 50 percent of the traits. The female holds the egg and the male holds the sperm which makes up 50 percent for each parent.
No, because boys can look like their moms.	No, girls do not inherit more traits from their mom than their fathers because traits come in pairs. One from the father and one from the mother. The mother or the father may give more dominant traits or recessive genes but each parent gives the same amount of traits.

included new concepts in their responses – for example, characteristics of sex cells, genes, alleles, and chromosomes (39%).

○ Discussion & Implications

The analysis of embedded assessments showed that this group of students accomplished higher levels of understanding during instruction with the WISE units. Responses suggested that fifth-grade students systematized their understanding of cells as the basic units that make up multicellular organisms. An important proportion of students also recognized basic aspects of trait inheritance, namely that traits are equally inherited from both parents.

Seventh-grade students integrated the new content with ideas they built on their previous knowledge and provided more details to their explanations. They were able to characterize cells by describing their genetic material, to explain characteristics of cell division and some of its implications, to distinguish between sexual and asexual reproduction, and to explain how traits are inherited by using cell components. Thus, students' responses to embedded assessments in fifth and seventh grades provided evidence that most students gradually changed their non-normative ideas, such as the belief that children do not inherit their traits equally from their parents (Kargbo et al., 1980; Terwogt et al., 2003).

Our results also confirm that students still struggled to distinguish among genes, alleles, chromosomes, and DNA, as prior research has indicated (e.g., Banet & Ayuso, 2000; Lewis & Wood-Robinson, 2000; Shaw et al., 2008), especially when making connections among topics of cells and heredity in order to explain complex phenomena. In some cases, students' responses were fragmented, lacking adequate sophistication necessary to explain, for example, the implications of the meiosis process on trait inheritance and diversity (Williams et al., 2012). These findings imply that the design curriculum materials and their related assessments need to address more explicitly the topics with which students struggle.

The findings of this study provide information to researchers and curriculum developers for the design and development of instructional materials to help teachers scaffold student understanding,

address students' non-normative ideas, and adequately connect the different pieces of learning into sophisticated explanations. Moreover, student responses to embedded assessments suggest that upper-elementary and early-middle-school students can adequately progress in learning complex topics about inheritance and that, therefore, these topics may be included and detailed in teaching standards for those grades as well as in instructional design.

When upper-elementary and early-middle-school students are involved with innovative, technology-enhanced, sequenced instructional materials such as WISE, they are able to explain and solve problems that imply the use of complex concepts of cells, reproduction, and inheritance – topics traditionally included at the secondary level (Banet & Ayuso, 2000; Venville et al., 2005). To the extent that instruction promotes adequate understanding of these topics in early grade levels, students may build the scientific ideas that will ultimately be used in high school biology courses. For example, the NRC's science education framework recommends that in grade 12 students understand how a DNA molecule regulates gene expression or explain the contribution of sexual reproduction to increased variation of traits between parents and offspring (NRC, 2012).

We recognize the limitations of our study. First, we are only describing students' understandings within each grade level, but not tracking students' performances from fifth to seventh grades. Moreover, we are not comparing students' performance between both grade levels, nor are we comparing the effectiveness of technology-enhanced versus traditional instruction. Finally, this study was conducted in only one school district, which has adopted the WISE heredity curriculum materials for classroom instruction.

For future research, we are interested in studying the connections between embedded and summative assessments to determine student progress over the units. We are redesigning instructional materials to (1) better address complex ideas in biology at both grade levels, (2) create embedded assessments that are linked with learning goals, and (3) provide more opportunities for students to write scientific explanations and work with scientific models to develop more integrated understandings.

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