Developing and Evaluating an Eighth Grade Curriculum Unit that Links Foundational Chemistry to Biological Growth:
Changing the Research-based Curriculum

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Abstract

Much of modern biology has become increasingly chemical in character. Not surprisingly, students often have trouble understanding key ideas in biology because they lack foundational chemistry ideas. AAAS and BSCS are collaborating to develop and study a curriculum unit that supports students' ability to explain a variety of biological processes involving growth in chemical terms. The unit provides conceptual coherence between chemical processes in nonliving and living systems through the core idea of atom rearrangement and conservation during chemical reactions, which is critical for understanding how growth occurs while conserving matter. An initial draft of the unit was pilot tested at two schools in 2011. The results of the pilot test were used to revise the unit. In the spring of 2012, the revised unit and teacher materials was field tested. In this paper we will describe the iterative development process and the research that supports it. We will describe the Year 2 curriculum and, specifically, highlight how the curriculum enacts its four key design principles. Selected findings will be discussed that informed subsequent revisions during the final year of the project.

Introduction

Student understanding in science. Evidence from large-scale student assessments makes it clear that U.S. students are not well prepared in science. For example, on the NAEP 2011 science assessment, only 32% of eighth grade students scored at or above the proficient level, whereas 35% performed below basic (National Center for Education Statistics, 2012). While these data show improvement from the 2009 science assessment data, there is still a significant number of students entering high school with below basic understanding of science. Furthermore, on the 2009 NAEP science assessment only 21% of 12th grade students reached proficient, and 40% performed below basic (National Center for Education Statistics, 2012), indicating that little more is learned during high school. Today's middle and high school students must be better prepared, whether to succeed in college-level science or just to participate productively in a society becoming increasingly reliant on scientific and technology literacy.

Although U.S. students are not performing well in any of the sciences, we are particularly concerned about students' low achievement on topics that are essential for further study of biology (e.g., Andersson, 1986; Mohan *et al.,* 2009). The National Research Council has called attention to the increased dependency of biology on chemistry, noting that this "trend will continue, as more and more biological phenomena are explained in fundamental chemical terms" (2003, p. 136). Anderson *et al.* (1990) claim that "students' difficulties in understanding biological processes are rooted in misunderstandings about concepts in the physical sciences, such as conservation of matter … and atomic molecular theory, [that] were not addressed in instruction" (p. 775). Similarly, we have found that student misconceptions related to these topics and biological growth are prevalent at the middle and high school levels (AAAS Project 2061, n.d.). Taken together, these findings suggest that there is a need for more-effective curriculum materials that can provide students with a foundation of chemistry knowledge on which to build new biology knowledge.

The role of curriculum materials. Curriculum materials are ubiquitous in science classrooms. Ball and Cohen (1996) describe curriculum materials as having an "intimate" relationship with teaching, due in part to their accessibility as a teacher resource. Ball and Cohen further argue that, "Unlike frameworks, objectives, assessments, and other mechanisms that seek to guide curriculum, instructional materials are concrete and daily. They are the stuff of lessons and units, of what teachers and students do … Not only are curriculum materials well-positioned to influence individual teachers' work, but, unlike many other innovations, textbooks are already scaled up' and part of the routine of schools. They have 'reach' in the system" (1996, p. 6).

The notion that instructional materials directly influence the learning process is supported in numerous studies (e.g., Begle, 1973; Usiskin, 1985; Schmidt *et al.*, 1997). Likewise, the National Research Council (NRC) suggests that effective science curricula can be valuable in improving student interest and achievement in science (NRC, 2007). Research-based instructional materials have the potential to transform teaching and learning in science (Lee *et al.*, 2005; Lynch, Kuipers, & Pyke, 2005; Lynch, Kuipers, Pyke, & Szesze , 20052005). Nevertheless, several factors limit the promise that curriculum materials hold for advancing science teaching and learning. Studies evaluating science curricula indicate they are "fragmented," lacking coherence, and not articulated through a sequence of grade levels and cover many topics superficially without attention to coherent and rigorous conceptual frameworks (Roseman *et al.*, 1997; Kesidou & Roseman, 2002; Stern & Roseman, 2004; Roseman *et al.*, 2010). Few curriculum materials are organized to address the notion of learning science as a developmental progression or to address in-depth the comprehensive standards as outlined by documents such as the *National Science Education Standards* (NRC, 1996), the *Benchmarks for Science Literacy* (AAAS, 1993), and more recently, *A Framework for K-12 Science Education* (NRC, 2012). And curricula rarely direct students to reflect upon key understandings (Kesidou & Roseman, 2002).

The Toward High School Biology Project. The Toward High School Biology Project is a three-year collaboration between AAAS Project 2061 and BSCS focused on the development and study of a six-week middle school curriculum intervention that connects core chemistry and biology ideas in order to help students build a strong conceptual foundation for their study of biology in high school and beyond. The curriculum intervention consists of instructional materials for both students and teachers and a suite of hybrid (face-to-face and online) professional development materials. We have also developed a suite of measures to study student knowledge and skills, teacher knowledge and skills, and feasibility of using the curriculum as intended. The findings of these measures are used to improve the coherence and usability of the curriculum toward helping students to understand and apply chemistry ideas in explaining a range of biological contexts involving growth.

The unit differs from existing materials in several ways. First, the unit promotes students' sense making through a coherent presentation of the science ideas. Second, the unit addresses the most common and persistent misconceptions students have about chemical and biochemical changes and their molecular-level explanations (Smith & Anderson, 1986) and provides a solid grounding in chemical reactions and conservation in physical science phenomena and relates them to life science phenomena. Third, the unit engages students with relevant real-world phenomena and helps them to develop scientific explanations. For each phenomenon students relate macroscale observations to the underlying molecular representations. Finally, the unit takes advantage of physical models and other molecular representations to guide students' sense making, including LEGO® bricks, ball-and-stick model kits, and images of ball-and-stick and space-filling models.

We are currently in the final year of the project. In the first year, we pilot tested an initial version of the unit with a small number of schools (Herrmann Abell *et al*., 2012). Data from the pilot test was used to revise the unit in preparation for the field test in Year 2. This paper reports on the iterative development of the curriculum unit, focusing on the Year 2 curriculum unit, findings, and implications of those findings for future revisions.

Other papers in this set detail the selection of core ideas and practices (Roseman *et al*., 2013), the design and development of teacher support materials and professional development (Kruse *et al*., 2013), measures of students' understanding and field-study results (Herrmann Abell *et al*., 2013), and measures of teachers' knowledge of the content and curriculum and field-study results (Flanagan *et al*., 2013). The Toward High School Biology Project is funded by a U.S. Department of Education IES Goal 2 Development and Innovation grant to develop and study the feasibility and usability of the curriculum and a suite of teacher-support materials.

Methodology

Research-based curriculum design. Our iterative, multifaceted development process carefully integrates design with current research findings, which is an approach that is well aligned with the theory of research-based curriculum design described initially by Clements (2007) for mathematics and more recently by Carlson and Taylor (submitted) for science.

Guiding the design and development of the curriculum unit is a theory of change positing that students' science understanding develops from (a) having a wide range of experiences with the natural world that are explainable by a coherent set of ideas and (b) having an opportunity to interpret and make sense of what they experience in terms of those ideas. Experience alone is not enough to generate conceptual understanding. Students must also be guided in thinking about what they observe and in connecting their observations about instances to general principles and to what they already know. This view draws from constructivist (Bransford *et al.*, 2000), conceptual change (Posner *et al.*, 1982), and situated cognition theories of learning (Brown *et al.*, 1987; Collins *et al.*, 1989).

Key findings from the AAAS Textbook Evaluation Study (Roseman *et al.*, 1997; Kesidou & Roseman, 2002), the Trends in Mathematics and Science Study (TIMSS) (Schmidt *et al.*, 1997, 2001), the TIMSS Science Video Study (Roth & Garnier, 2007), and the research syntheses of *How People Learn* (Bransford *et al.*, 2000) and *Knowing What Students Know* (Pellegrino *et al.*, 2001) provide clear guidance for the development of effective materials. These reports suggest that curriculum materials in the United States could be more focused by having a storyline organized around key concepts; be more coherent by having explicit connections between ideas; and be more rigorous by setting high standards for learners cognitively and metacognitively.

This research underpinning our theory of change influenced the articulation of a set of design principals intended to help guide students in constructing their own understandings of the articulated learning goals. The curriculum is designed to

1. provide students with opportunities to experience phenomena that can serve as evidence for the science ideas and/or for their explanatory power;
2. provide a variety of models of both objects (atoms and molecules) and processes (atom rearrangement and conservation during chemical reactions) to make abstract ideas about chemical reactions more concrete;
3. provide guidance in observing, interpreting, and reasoning about phenomena and models;
4. make visible a coherent science content storyline for the molecular basis of growth and repair in living organisms; and
5. apprentice students in the practice of constructing explanations with modeling, scaffolding, and fading.

Phases of curriculum development integrated with research. The paper set focuses on Year 2 of our project, which corresponds with Phases 3 (Revision) and 4 (First Field Test) below. The following briefly outlines our iterative curriculum development process and the role of the research throughout.

Year 1

Phase 1: Design and Development

Using a backwards design approach (Wiggins & McTighe, 2005), the development team first articulated clear learning goals, boundaries, and common and persistent misconceptions to guide the design of two units (initially a chemistry unit and a biochemistry unit, which were merged into a single unit in Phase 4 to improve coherence) and the student and teacher research measures. The sources of potential learning goals, boundaries, and misconceptions included the AAAS *Benchmarks for Science Literacy* (AAAS, 1993), AAAS Science Assessment Study data (AAAS Project 2061, n.d.), and the extensive misconceptions literature base.

Following this articulation, writers prepared conceptual flow graphics for each unit and chapters within the unit. These conceptual flow graphics represented a visual outline of the unit focusing on a coherent storyline and connections to the big idea of the chapter. Internal reviews focused on conceptual coherence and emerging storyline within each unit and across the two units.

The development team drafted a prototype version of the curriculum materials, including writing and art development that integrated phenomena, data, and models with sense-making strategies in each lesson developed. Writers tested activities with students in grades 5–9 outside of the school setting. Students provided feedback on the activity as well as critical information about student thinking related to the activities.

Phase 2: Pilot

The developed curriculum materials were piloted sequentially in two schools offering a diverse range of school context and student demographics. In the first school, the writers taught one class period and then observed and coached as the teacher taught the remaining periods. From this work, teacher materials were drafted to support the second pilot teacher. Formative data, including student notebooks, teacher surveys and interviews, and researchers' classroom observations, were collected and used to inform revisions in Phase 3. Internal and external reviews of the student and teacher materials by content and pedagogical experts using the Project 2061 Textbook Evaluation Criteria also informed revisions in Phase 3. Herrmann Abell *et al.* (2012) describe the initial version of the unit (Phase 1), and summarizes the findings from the pilot (Phase 2) and how they were used to revise the curriculum (Phase 3).

Year 2

Phase 3: Revision

The revision phase mimicked the development phase, but was informed by the pilot data. All materials—student materials as well as teacher support materials—were revised in response to the findings of the pilot. Revisions focused on improving student learning, often through coherence and quality of support for teachers. In addition, professional development was designed to support the revised curriculum, as described by Kruse *et al.*, 2013.

The revisions were initiated at a conference of the research and development team and pilot teachers. In that conference a framework was drafted, articulating the ideas (claims) students were intended to make in each lesson and the evidence and reasoning about specific phenomena, data, and models that would provide support for those claims. This framework was internally evaluated and revised in an effort to improve coherence. Once satisfied, work commenced on the revisions of the curriculum materials themselves.

Phase 4: First Field Test
A field test was conducted with a relatively small but diverse sample of eight teachers and their 677 students in the East Coast and in the West. The purpose of the field test was to understand whether the fundamental structure of the program was feasible to implement in a variety of ordinary classroom settings, to conduct preliminary tests of impact on student achievement and teacher learning, and to collect data to further inform revisions. The data sources and analyses included the following:

- **Quality of the student materials.** A subset of Project 2061's Textbook Evaluation Criteria were used to analyze the student materials. Findings of the analysis of coherence and content alignment to learning goals are described by Roseman *et al.* (2013).
- **Quality of the teacher materials and professional development.** A subset of Project 2061's Textbook Evaluation Criteria were used to analyze the coherence and quality of support for teacher learning that are provided by teacher materials (TE) and professional development (PD). A teacher pre-, mid-, posttest assessed teachers' knowledge and skills needed to teach the unit across the subscales of content coherence and pedagogical support for student learning. The measure and findings are described by Flanagan et al. (2013).
- **Feasibility of use.** Teacher pacing logs, student work, and teacher online reports of their students' progress were used to find out what lessons and activities teachers are using and how much time it is taking them. Findings are summarized in Roseman *et al.* (2013). We also videotaped four lessons in one of each teacher's classes and analyzed them according to the criteria and accompanying indicators that best predicted student learning in AAAS' previous IERI study: Guiding student interpretation and reasoning (Wilson & Roseman, 2012).
- **Student pretests and posttests.** A multiple choice assessment was developed and piloted that aligned with the articulated learning goals, boundaries, and common and persistent misconceptions. The measure and findings are described by Herrmann Abell *et al.* (2013).
- **Student interviews.** A small number of students were interviewed during and after the unit to assess how consistent their performance on the student test is with their oral performance on interview questions.
- **Student classwork.** Students' written work is analyzed to determine what lessons and activities were actually completed and serve as an indicator of what students understand.

Year 3
Phase 5: Second Field Test Cycle
Phases 3 and 4 were repeated during the 2012–2013 school year. In addition to using Year 2 findings to inform changes in the curriculum, significant effort was expended to more closely align the unit to the related disciplinary core ideas, crosscutting concepts, and science practices as they are described in *A Framework for K-12 Science Education* (NRC, 2012). In the spring of 2013, we are planning a small cluster randomized trial with six teachers. Our hope is that this small, low-power study will indicate that the unit has promise when compared with "business as

usual." We are studying the unit in the classrooms of three returning teachers from Year 2 and three new teachers.

Subsequent sections of this paper will describe the revised student materials that were tested in Phase 4. While considered part of the curriculum materials, the teacher edition of the materials is discussed elsewhere in the broader context of teacher support and professional development (Kruse *et al.*, 2013). This paper will summarize a few selected findings that illustrate the iterative nature of the development and the role of research findings. We will also consider how these findings guided critical revisions made in the final year of the curriculum. Herrmann Abell *et al.* (2013) and Flanagan *et al.* (2013) provide elaborations of the findings of student learning and findings of teacher learning, respectively.

The Year 2 Curriculum

The Year 2 (Phase 3 and 4) curriculum consisted of a single unit—11 chemistry lessons followed by 14 biology lessons that build upon the chemistry lessons—providing a coherent treatment of the overarching goal:

> Students will be able to use the idea that all matter is made out of atoms to explain growth and repair in living organisms (plants and animals). In order to grow and repair body structures, plants and animals build polymers through chemical reactions from subunits (monomers) that plants make through other chemical reactions. Through all this, atoms are rearranged and conserved.

Learning goals. The unit targeted science ideas that are included in the 6–8 grade band in the science standards of most U.S. states, including those states in which the curriculum was field tested. These ideas are also found in the *2011 NAEP Science Framework* (National Assessment Governing Board, 2008), *Benchmarks for Science Literacy* (AAAS, 1993), and, more recently, *A Framework for K-12 Science Education* (NRC, 2012). The targeted chemistry and biology ideas are listed in Tables 1a and 1b, respectively.

The curriculum unit is divided into four chapters, each of which develops students' understanding of a learning goal that synthesizes one or more of the targeted chemistry and/or biology ideas described in Tables 1a and 1b. Chapter 1 addresses new substance formation through atom rearrangement during chemical reactions. Chapter 2 addresses mass conservation through atom conservation during chemical reactions. Chapters 3 and 4 apply and build upon the key ideas addressed in Chapter 1 and Chapter 2. Chapter 3 addresses the chemical basis of animal growth. Chapter 4 addresses the chemical basis for plant growth.

Table 1a. Target science ideas (chemistry)

Science Ideas (Chemistry)
New substances form during chemical reactions.
Every substance has a unique set of properties, such as color, odor, density, melting point, and boiling point. Scientists can measure these properties and use them to tell one substance from another.
Atoms rearrange during chemical reactions.
For many substances, a molecule is the smallest part of that substance. A molecule is made up of two or more atoms connected together in a specific arrangement. Atoms and molecules are extremely tiny—so tiny that we cannot even see them under the highest-powered microscopes. Substances that we can see are made up of huge numbers of atoms and molecules. There are many different types of atoms that combine in different ways to make up the molecules of different substances. The properties of a substance are determined by the different type, number, and arrangement of atoms that make up the molecules of the substance. We can represent atoms and molecules with different types of models. Models can show some aspects of the real thing but not all aspects. Different models can show different things or provide different information about molecules. During chemical reactions, atoms that make up molecules of the starting substances separate from one another and connect in different ways to form the molecules of the ending substances. The starting substances and ending substances are made up of the same types of atoms and the same number of each type. Not all atoms of the molecules of the starting materials rearrange during a chemical reaction. Sometimes when forming new substances, groups of atoms stay together and only a few atoms from each starting molecule rearrange. Small molecules made up of carbon chains (monomers) can link together during chemical reactions to form large molecules (polymers) and water molecules. Monomers usually have groups of atoms—either oxygen and hydrogen atoms or nitrogen and hydrogen atoms—at two places on the molecule that are important for linking the monomers. Atoms still rearrange when polymers form, even though only a few are actually rearranged. Even though only a few atoms rearrange, polymer formation is a type of chemical reaction. The polymer is a new substance and has different properties than the monomers from which it formed.
Mass is conserved in chemical reactions.
The amount of matter is constant during chemical reactions. If all of the reactants and products are measured, the mass of the reactants is the same as the mass of the products. The mass of a particular atom does not change, so a certain number of that type of atom will always have the same mass. Atoms are neither created nor destroyed during chemical reactions, so the total number of each type of atom remains the same. Because the mass of a particular atom stays the same and because the total number of each type of atom stays the same, the total mass of the matter stays the same when atoms are rearranged during chemical reactions.
Changes in measured mass don't violate conservation.
If the measured mass changes during a chemical reaction, it is because one or more substances, usually gases, have entered or left.

Table 1b. Target science ideas (biology)

Science Ideas (Biology)
Animal growth requires chemical reactions.
The body structures of animals are made mostly of proteins. Proteins are polymers made of amino acid monomers. The amino acid monomers, and therefore the proteins made from them, are composed mainly of carbon, hydrogen, oxygen, and nitrogen atoms. Growth, repair, and replacement of animal body structures all involve chemical reactions during which proteins from food are used to make other proteins that become part of their body structures. The process by which proteins from food become part of animals' body structures involves chemical reactions in which the proteins from food are broken down into amino acid monomers, and these monomers are used to build new protein polymers that make up body structures. Atoms from the molecules that animals eat do not get incorporated into body structures without first going through chemical reactions.
Animal growth doesn't violate conservation principles.
When animals grow, they increase in mass. This increase in measured mass comes from the incorporation of atoms that were originally outside of the animals' bodies.
Plant growth requires chemical reactions.
The polymers that make up plants' body structures are mostly carbohydrate polymers. A few plant parts, like seeds, contain large amounts of protein polymers. Carbohydrate polymers are made of glucose monomers. Plants make the glucose monomers they use to build carbohydrates using a chemical reaction between carbon dioxide and water molecules. The process of making glucose monomers involves linking together carbon atoms that come from carbon dioxide. Oxygen molecules are another product of the chemical reaction that plants use to make glucose. Growth, repair, and replacement of plant body structures involve chemical reactions during which glucose molecules are used to make carbohydrate polymers. These carbohydrate polymers become part of the plant's body structures. Plants use a chemical reaction involving glucose molecules and nitrogen atoms to make amino acid monomers. Plants use these amino acids to build protein polymers that become part of their body structures. The nitrogen that plants use to make proteins comes from nitrogen-containing molecules that plants take in from the soil. Plants use minerals to grow, but minerals add a very small amount of mass to plants as they grow. Most of the increase in the measured mass of plants does not come from soil, water, or minerals. Most of the mass of plants comes from carbon dioxide.

The unit also targeted two science practices—using models and constructing explanations—that play a critical role in supporting students in understanding phenomena involving the growth of animals and plants and underlying atomic/molecular processes. NRC's *Framework for K-12 Science Education* specifies practices only at grade 12; however, aspects of those practices that are appropriate for and helpful to eighth grade students in this curriculum unit are highlighted below in bold font.

Developing and Using Models (NRC, 2012 p. 58)
By grade 12, students should be able to

- **Construct drawings or diagrams as representations of events or systems**—for example, draw a picture of an insect with labeled features, represent what happens to the water in a puddle as it is warmed by the sun, or represent a simple physical model of a real-world object and use it as the basis of an explanation or to make predictions about how the system will behave in specified circumstances.
- **Represent and explain phenomena with multiple types of models—for example, represent molecules with 3-D models** or with bond diagrams—**and move flexibly between model types when different ones are most useful for different purposes.**

Practice 6, Constructing Explanations and Designing Solutions (NRC, 2012 p. 69)
By grade 12, students should be able to

- **Construct their own explanations of phenomena using their knowledge of accepted scientific theory and linking it to models and evidence.**
- **Use** primary or secondary **scientific evidence and models to support or refute an explanatory account of a phenomenon.**

More details about the selection of the learning goals can be found elsewhere (Roseman *et al.*, 2013).

Enacting the design principles. Here we describe the ways in which the design principles are manifested in the Year 2 curriculum unit.

Design Principle 1. The curriculum is designed to provide students with opportunities to experience phenomena that can serve as evidence for the science ideas and/or for their explanatory power. The lessons engage students in observing and interpreting a variety of phenomena and secondhand data to both develop and apply new ideas. For example, students observe the formation of nylon thread, providing evidence that chemical reactions have occurred because a new substance forms with properties distinct from those of the starting substances. In other lessons students examine experimental data showing that radio-labeled amino acids fed to animals are later detected in the muscles of those animals, which is used as evidence that amino acids from foods are used to build protein polymers making up our muscles. Table 2 describes phenomena (including secondhand data) used in the unit. The two phenomena from nonliving contexts that are used as analogies to phenomena occurring in living contexts are rust formation and nylon formation (bolded).

Table 2. Phenomena and data

Phenomena and data in nonliving contexts	Phenomena and data in living contexts
• **Rust formation when steel wool is exposed to air (with and without mass data)** • **Nylon formation when hexamethylenediamine and adipic acid are mixed** • Milk of magnesia formation when Epsom salt and ammonia solutions are mixed (with and without mass data) • Carbon dioxide formation when baking soda and vinegar are mixed (with and without mass data) • Table salt formation from chlorine and sodium • Hydrogen peroxide decomposition • Dissolution of carbon dioxide in soda water • Combustion of methane • Combustion of a log (cellulose) • Patina formation on the Statue of Liberty	• Growth (puppy to dog, sapling to tree, hair, egg to a chick) • Repair (healing wound, lizard tail regeneration, sea star ray regeneration) • Animals eating their food (chameleon eating lizard, snake eating egg) • Protein-fat-carbohydrate compositions of animal-based foods • Radio-labeling experiments in animals (muscle-wasting studies in men, growth-hormone studies in pigs) • Protein-fat-carbohydrate compositions of plant-based foods • Radio-labeling experiments in plants (photosynthesis, amino acid formation) • Van Helmont's willow tree experiment • Fertilizer and soil composition • Crayfish molting/shell formation

Design Principle 2. The curriculum is designed to provide a variety of models of both objects (atoms and molecules) and processes (atom rearrangement and conservation during chemical reactions) to make abstract ideas about chemical reactions more concrete. The lessons engage students in manipulating and reasoning about a variety of molecular modeling activities (e.g., LEGO bricks, ball-and-stick models, images of ball-and-stick and space-filling models, chemical and structural formulas, and equations). Using a variety of models gives students different ways to represent and work with abstract ideas and to synthesize or connect seemingly disparate experiences and ideas. For example, students can reason from models that two monomers used in the nylon reaction are, indeed, different molecules with different types and arrangements of atoms than the nylon polymer they form. And, it is through the rearrangement of a few atoms from each monomer model that water and nylon are formed, yet *all* atoms (and therefore mass) are conserved during the chemical reaction. Table 3 (next page) summarizes key models and representations included in the unit.

Design Principle 3. The curriculum is designed to provide guidance in observing, interpreting, and reasoning about phenomena and models. The intentional selection and sequencing of tasks (prompts) and questions support students in the making of intended observations and in making sense of those observations, providing opportunities to develop science ideas targeted in the lesson. The tasks (prompts) and questions are deliberately sequenced in ways that allow students to first tend to individual instances and then synthesize or generalize across those instances to develop their understanding of the science idea. They have opportunities to compare their idea with established science ideas. Later the established science idea is applied to new contexts. For example, students use LEGO models to sequentially model and reason about chemical reactions involving 1) formation of rust from iron and oxygen, 2) formation of carbon dioxide from baking soda and vinegar, and 3) formation of milk of magnesia from Epsom salt and vinegar.

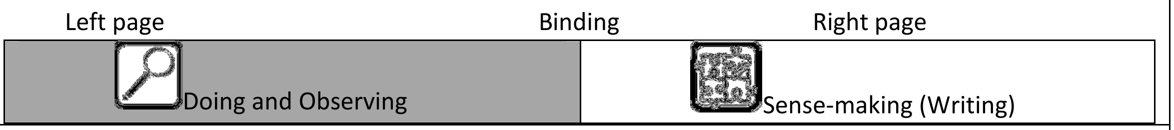
Through questions following each chemical reaction, they are called to notice that in each case, new molecules are formed from the LEGO bricks of starting molecules, no additional LEGO bricks are required, and none are leftover. After completing the modeling sequence, students are prompted to synthesize a "rule" that describes chemical reactions through atomic/molecular processes: During chemical reactions atoms are rearranged and conserved (they are not created or destroyed, and atoms do not turn into different atoms). Questions prompt students to notice that sometimes groups of atoms stay together during chemical reactions. In later lessons, the curriculum guides students in referencing these observations and ideas and applying them to contexts of polymer formation in both nonliving and living contexts.

Table 3. Models and representations

Models in nonliving contexts	Models in living contexts
• LEGO, ball-and-stick, and space-filling models, chemical formulas, and structural formulas of **molecules** of various substances • LEGO models representing starting and ending substances of chemical reactions: o Rust formation when steel wool is exposed to air (with atom counting and mass data) o Milk of magnesia formation when Epsom salt and ammonia solutions are mixed (with atom counting and mass data) o Carbon dioxide formation when baking soda and vinegar are mixed (with atom counting and mass data) o Table salt formation from chlorine and sodium o Hydrogen peroxide decomposition o Dissolution of carbon dioxide in soda water • Ball-and-stick models to represent **chemical reactions**: o Nylon formation when hexamethylene-diamine and adipic acid are mixed • Space-filling models to represent **chemical reactions**: o Combustion of methane o Combustion of hydrogen	• Ball-and-stick models of **molecules** o Amino acids o Cellulose o Starch • Ball-and-stick models to represent **chemical reactions:** o Protein digestion to amino acids o Protein formation from amino acids o Protein formation with radio-labeled amino acids o Glucose formation from carbon dioxide and water o Cellulose formation from glucose

Design Principle 4: The curriculum is designed in ways that make visible a coherent science content storyline for the molecular basis of growth and repair in living organisms. Coherence is developed within and across lessons by 1) establishing the learning goal, 2) selecting and sequencing activities based on relevant phenomena and atomic/molecular representations that support the learning goal, 3) explicitly linking science ideas to the activities, and 4) connecting science ideas within and across lessons (Roth, 2009). Table 4 provides a summary of the lesson phases and their function, as they relate to establishing coherence. Most phases of a lesson include tasks and/or questions that guide students in doing one or more of the following: 1) linking phenomena and models of those phenomena to the science ideas, 2) linking science ideas within and across lessons, and/or 3) using and applying science ideas developed in nonliving contexts to living contexts.

Table 4. Lesson elements and function

1. Lesson Question
We have designed each lesson so that the title is the lesson key question. The lesson key question aligns with the lesson's main learning goal and frames the students' inquiry. We crafted the questions to balance the opportunity for students to possibly generate a range of responses when posed at the end of the lesson, making it a useful diagnostic tool for the teacher, yet remain vague enough to not "give away the answers" when posed at the beginning of the lesson.
2. Purpose
The purpose section situates the lesson in the content storyline by making links between science ideas of previous lesson(s) and the learning goals or questions of the current lesson. The purpose section also does not "give away the answers," but provides students with some sense of what they will be working toward understanding in the lesson.
3. Collecting and Interpreting Observations and Data
This section provides opportunities for students to both observe and make sense of phenomena and models in order to develop ideas. Activities are framed by the *Getting Started* and *Pulling It Together* sections to support students in connecting ideas and activities before and after each activity (Roth & Garnier, 2007; Roth, 2009). *Getting Started* often elicits students' ideas and predictions about phenomena or models that will be explored in the activity. *Pulling It Together* provides an opportunity for students to construct one or more science ideas from the observations and interpretations made during the activity. When students are working the *Getting Started* and *Pulling It Together*, they often work with a partner, small group, or participate in a whole-class discussion. The activities within the curriculum unit are formatted using a double page design that helps students more easily link their observations (left page) with the sense-making opportunities (right page). 
4. Summarize, Reflect, and Connect.
This series of questions provides opportunities for students to individually 1) revisit and answer lesson questions or related questions to summarize their current understanding and/or new learning, 2) use and apply the ideas they are developing to a new context or phenomenon, and/or 3) begin to link the ideas to next lesson(s) or chapters.
5. Lesson Homework: Identifying Examples of Science Ideas
At critical points in the unit, particularly after students have developed ideas based on phenomena and/or models, homework assignments provide opportunities for students to compare the ideas they are developing with established science ideas and find examples from their work that support the science ideas.
6. Stop and Think
These questions are used after a short passage of text to help students 1) make sense of ideas presented in text, 2) encourage students to ponder what they have just read in manageable chunks, and/or 3) use and apply the ideas they have read in the text. These will sometimes follow lesson homework, providing more opportunities to use and apply the science ideas.

Establishing coherence across chemistry and biology often involves relating seemingly unrelated phenomena in the nonliving and living contexts. In particular, phenomena involving polymer formation and phenomena involving open systems that use matter from the surroundings to make new matter during chemical reactions are linked across both contexts. The following list provides examples of tasks and/or questions in which ideas developed through nonliving contexts are used in the sense-making of phenomena in living contexts. In each of them, the ideas developed through the sense-making around phenomena.

- Ch. 3 Compare making a nylon jacket to making an animal body.
  Question: How is making an animal body similar to making a nylon jacket?
- Ch. 3 Compare rust formation and a sea star regenerating a ray.
  Question: How is growth in animal bodies like rusting?
- Ch. 4 Compare making a nylon jacket to making a tree.
  Questions: What is similar about the chemical reaction that makes nylon and the chemical reaction that helps to make trees?
- Ch. 4 Compare rust formation to plant and animal growth.
  Questions: Why does the mass of steel wool/animal/plant increase? Where does the mass come from to make rust/animals/plants?

Design Principle 5. The unit is designed to apprentice students in the practice of constructing explanations with modeling, scaffolding, and fading. For example, four of the lessons (one per chapter) focused on helping students "construct explanations of phenomena using their knowledge of accepted scientific theory and linking it to models and evidence" (NRC, 2012, p. 69). The students were first introduced to the elements of an explanation—claim, evidence, and reasoning (McNeill & Krajcik, 2012)—in a chart scaffold that is used to organize students' thinking and writing. Each element of an explanation is described (what it is). Two hypothetical explanations—one good, one needing improvement—are juxtaposed to help students establish their criteria for "complete" explanations. The first two explanation lessons follow the pattern of model then scaffold. The first activity models how to build explanations. The second activity scaffolds students in developing their own explanation. In the later explanations lessons (and three additional lessons containing an activity that allows students to practice writing explanations) the scaffolds fade. Table 5 describes this apprenticeship in more detail.

Table 5. Modeling, scaffolding, and fading explanations

Model	Scaffold	Fade
1. Hypothetical students identify and organize data that serve as evidence for a claim.	1. Students guided to identify and organize data that serve as evidence for the claim.	1. Students prompted to construct explanations with Claim, Evidence, and Reasoning with chart scaffold.
2. Hypothetical students represent the change with atomic/molecular representations (words, formulas, and images/models).	2. Students guided to represent the change with atomic/molecular representations (words, formulas, and images/models).	2. Students prompted to construct an explanation with Claim, Evidence, Reasoning without chart scaffold.
3. Hypothetical students construct an explanation with Claim, Evidence, and Reasoning chart scaffold.	3. Students guided to construct an explanation with Claim, Evidence, and Reasoning chart scaffold.	3. Students prompted to write an explanation, or explain without reminders for claim, evidence, and reasoning.
4. Students evaluate the hypothetical students' explanation with established criteria.	4. Students evaluate their own/peers' explanations with established criteria.	4. Students evaluate their own/peers' explanations with established criteria.

Selected Findings and Implications for the Year 3 Curriculum

Here we illustrate how the various data sources and analyses included in the study have informed the iterative development process.

Balancing Coherence and Feasibility. Much effort has been expended in finding the optimal balance of coherence in the storyline of the unit with feasibility to teach the unit as intended (e.g., completion). In the pilot test, for example, we determined that the short length of the unit (originally 4 weeks) and the scope of student misconceptions about energy revealed in interviews and classroom observations/video prevented us from adequately addressing the "energy" part of the storyline. The pilot materials had limited the treatment of energy to the idea that atoms do not turn into energy and energy does not turn into atoms. We learned that while many students could use this "rule," they found it insufficient in persuading their classmates. Moreover, many students still lacked atomic/molecular ideas for thinking about matter changes during chemical reactions. Some students could name some processes that are chemical reactions or the result of many chemical reactions as an animal grows, but typically at the organismal level. Fewer students listed specific chemical reactions such as building proteins, making glucose, or building cellulose.

In the end, we eliminated the energy ideas and related phenomena from the Year 2 content storyline (e.g., combustion of butane, respiration of stored carbohydrates) to improve coherence around changes in matter. We also incorporated plant proteins and animal carbohydrates into the content storyline in an effort to make the matter storyline more coherent across animal and plant growth. However, feasibility measures (e.g., teacher logs, student work, and classroom video) indicated that the unit was too long for the time allotted. Some teachers did not reach the end of the unit. One teacher did not reach the biology lessons, and two teachers did not reach the lessons on photosynthesis and plant growth. Teachers generally followed the curriculum script for the chemistry lessons. As it became clear that they would not complete the biochemistry lessons if they maintained the intended pace, teachers either kept that pace and didn't finish or rushed through making significant cuts.

Students' confusions in the post-unit interview about the molecular basis of growth of animals and plants was not surprising given the feasibility findings. Students who did reach the end of the unit showed particular confusions that are likely the result of the final two lessons on plant proteins and animal carbohydrates intended to improve the storyline. Table 6 provides example responses from students from questions about proteins and carbohydrates. S1–S3 are responses from students in classes that did reach the end of the unit (albeit at a fast past and with significant teacher-driven deletion from lessons).

Table 6. Post-unit student interviews

Q1: What are proteins? What are they made up of? What kinds of organisms are made up (at least partially) of proteins (plants, animals, both, or neither)?	Q2: What are carbohydrates? What are they made up of? What kinds of organisms are made up (at least partially) of carbohydrates (plants, animals, both, or neither)?
S1: Proteins are made of glucose. Animals have lots of proteins.	S1: Carbohydrates are sugars or scientifically they are called glucose. Glucose is made of atoms and the elements are C H O. Animals and Plants are made of carbohydrates.
S2: No idea.	S2: They give us energy.
S3: Amino acids (make) proteins. They're the same thing. Or amino acids are proteins with – yeah, there the same thing. Animals, animals and plants I think.	S3: I think they have something to do with fat. They're energy, like, that you need, and if you have too much, it makes you chubby. No [about what kinds of organisms are made up of carbohydrates].
S4: Amino acids is a type of polymer for protein, and protein makes you grow muscle.	S4: [Carbohydrates are] Glucose?
S5: Plants use amino acids to make its roots stronger. Plants. Leaves. Lettuce.	S5: Animals are mostly made up of carbohydrates. Amino acids turn into protein polymers. And I guess protein polymers turn into carbohydrate polymers.

Herrmann Abell et al. (2013) report significant decreases in the mean item difficulties for animal growth and plant growth using racked data sets in their Rasch model of student pretests and posttests. Table 7 summarizes these excerpted findings.

Table 7. Racked method: Mean item difficulties

Idea		Mean	t	Significance
Animal growth (N = 9)	Pretest	0.66	8.91	<.001
	Posttest	–1.13		
Photosynthesis and Plant Growth (N = 11)	Pretest	0.97	4.99	<.01
	Posttest	0.11		

These data suggest that the ideas targeted by the items were learned by the students who participated in the unit. Incidentally, items targeting animal growth were among those with the largest decrease in difficulty. The decrease in the difficulties for photosynthesis and plant growth items suggest that despite rushing, and in some cases not completing all lessons that include the idea(s), the activities targeting these ideas had impact on students' learning.

For the sake of both coherence and feasibility, in our revisions for the Year 3 field test we have further streamlined the storyline so that the entire unit could be completed within six weeks of instruction. We focused on establishing the storyline of animal growth through protein digestion and new protein formation and plant growth through glucose synthesis and cellulose formation. In doing so we cut some ideas that were not as central to the overarching goal of growth in living things as defined above. And we eliminated activities, phenomena, and models that did not advance the storyline of growth. For example, the synthesis of amino acids from glucose monomers in plants, formation of plant proteins, and, generally, the story of carbon cycling from air to plants to animals through plant proteins were eliminated to reduce confusion between basic structural polymers of animals and plants. We hope these changes find the synergistic “sweet spot” of coherence and feasibility.

Distinguishing Total Mass from Measured Mass. In the Year 2 curriculum we revised the learning sequence significantly to better support students’ understanding that 1) total mass is conserved during chemical reactions even if the measured mass of the system changes and 2) changes in measured mass occur if, for example, gases (which are involved in the chemical reaction) can enter or leave the system. We argued that making this distinction between total mass and measured mass explicit with simpler systems in the nonliving contexts would help students understand that conservation is not violated during growth (increases in mass) in living things. Furthermore, providing students evidence that gases have mass would support their understanding that the mass of plants comes largely from carbon dioxide, a gas in the air.

In the first lesson of the new sequence students compared the initial and final masses of chemical reactions occurring in sealed containers, then opened the containers and compared the masses with that of the sealed container after, for example, a gaseous reactant entered and reacted to form more product, or a gaseous product left the container. In the last lesson of the learning sequence students modeled larger systems of the chemical reactions with LEGOs in a bag and related atom counts and mass of the sealed and opened bag “system” to their previous observations of the actual phenomena.

The curriculum posed the same two questions at the beginning and end of the learning sequence:

- What happens to the amount of matter (mass) during chemical reactions?
- Why does measured mass sometimes change when the container is opened?

Approximately 20 students’ notebooks were collected from each teacher. A review of students’ responses to the questions at the end of the learning sequence reveal that many students reasoned that the amount of matter stays the same during chemical reactions, but the mass will change if gases (which have mass) can leave or enter the system. Students tended not to use the terms “total mass” and “measured mass” in their responses, and in teachers’ analyses of the same notebooks, a few suggested that in class students still struggled with the distinction between the two.

Students’ notebook responses at the end of the learning sequence reflected a generally low but varied frequency of using atom-level mechanisms to explain conservation of (total) mass and changes in measured mass. Approximately 25% of the student notebooks reviewed referenced atoms and/or molecules, ranging from one of 20 students for one teacher to 9 of 20 students for another teacher. Several teachers’ written analyses of the same students’ notebooks suggested that many students understood and verbally discussed in class that when mass changed, not all of the atoms had been accounted for in initial or final mass measurements, suggesting potential inconsistencies between students’ thinking, talking, and writing.

Looking at student pre-post scores gives us another indicator of whether students were linking mass and atoms. Herrmann Abell et al. (2013) report significant decreases in the mean item difficulties for conservation of mass and conservation of atoms using racked data sets in Rasch models of student pretests and posttests. Table 8 summarizes these excerpted findings. It is noteworthy that three of the eight atom conservation items involved open systems. Distractor analysis revealed that after the unit fewer students selected distractors aligned to misconceptions about atoms being created during growth. These data suggest that the ideas targeted by the items were learned by the students who participated in the unit. Furthermore, in analyses of students' responses to open-ended items about the mass of a sealed bag containing molding bread, 14% of the students mentioned atoms in their explanations on the posttest versus only ~0.3% on the pretest.

Table 8. Racked method: Mean item difficulties

Idea		Mean	t	Significance
Mass is conserved (N = 4)	Pretest	0.86	7.88	<.01
	Posttest	–0.34		
Atoms are conserved (N = 8)	Pretest	0.65	9.78	<.001
	Posttest	–0.33		
Animal & Plant Growth and Conservation (N = 1)	Pretest	1.72		
	Posttest	0.74		

Taken together, these findings from the analyses of student notebooks and the student measures suggest that students' ability to correctly use ideas about atom conservation to explain mass observations increases after the unit. But they also suggest that students are more likely to make use of these ideas when prompted (through a question in the curriculum or an item choice in a student measure item). Thus, in our Year 3 revisions we paid careful attention to questions posed in the curriculum to improve students' use of ideas of atom conservation for explaining mass observations. For example, we now ask questions such as the following:

- How does rearranging atoms keep the total mass constant during chemical reactions?
- If atoms and total mass are always conserved during chemical reactions, why can measured mass change when the container is opened?
- When the mass increases, plants get bigger. What is happening to the number of atoms making up their bodies? Where do you think the atoms that a plant gains as it grows come from?

We also included a science idea that would reconcile conservation principles at the macro and molecular levels with observed changes in mass. Given students' difficulty reconciling the law of conservation of mass with observed mass changes in open systems, we decided to explicitly confront this seeming inconsistency through modeling activities and by elaborating upon changes in measured mass through a science idea:

> Science Idea #11: The *measured mass* of reactants and products is not always the same as the *total mass*. The measured mass changes if reactants or products (often gases) enter or leave an opened container. This is because atoms that make up reactants or products enter

> or leave the opened container. When measured mass changes, it is because we have measured the mass of all of the atoms involved in the chemical reaction.

Representations in the Unit. In the Year 2 curriculum we elected to exclusively use ball-and-stick models when using models to represent larger carbon-based molecules (e.g., monomers and segments of polymers) and chemical reactions involving these molecules. In student interviews, many students stressed the importance of "hands-on" activities in helping them learn. Many students said they liked the ball-and-stick model kits the best. Students claimed that the LEGO models were shaped differently from "regular molecules" and the way the bricks were stuck together obscured some of the connections between "atoms." Students also complained that LEGO models broke apart easily (even with the smaller molecules).

Our classroom observations and video indicated that, in general, teachers were engaging students in the modeling activities. However, some teachers enacted the modeling tasks in Chapters 3 and 4 (with ball-and-stick models) almost exclusively as teacher-led demonstrations after a challenging experience with protein digestion (e.g., some students completely dismantled the protein model instead of breaking and making a few connections to make amino acids; other students could not accurately reconnect the amino acids to build the protein models for the next period). In informal conversations between classes and during planning periods, two teachers suggested that these kinds of tasks require more class time and more extensive scaffolding than was found in the student edition.

In Year 3 we revised the student materials to increase the frequency that students engage in identifying monomeric units from ball-and-stick model images of polymer segments. We also increased the level of scaffolding when ball-and-stick physical models are used to ensure greater success in manipulating the models. For example, students were provided step-by-step routines for

- building large carbon-based molecules,
- contemplating manipulations with photographs of the models before conducting them with the physical models, and
- checking with the teacher for an "OK" to proceed with manipulating the models.

Kruse *et al.* (2013) also describe revisions to the suite of teacher support materials (e.g., online tutorials and how-to videos) that are intended to support teachers in apprenticing their students in learning the foundational science practice of using models.

Conclusions

This paper reported on the iterative development process of a curriculum intervention designed to support students' ability to explain a variety of biological processes such as growth in chemical terms. The unit engages students in observing, interpreting, and explaining relevant real-world phenomena by relating macroscale observations to the underlying molecular representations through a variety of physical models and other molecular representations. Here we described the Year 2 curriculum and, specifically, highlighted how the curriculum enacts its four research-based design principles. We illustrated how findings from a variety of teacher and student data sources informed revisions during Year 2 and the final year of the project.

The project has broader impacts for the field of science education at a critical time. As science educators begin to incorporate the recommendations in the National Research Council's *Framework for K-12 Science Education* and to prepare for the final release of the *Next Generation Science Standards*, this curriculum intervention serves as one of few models in which curriculum materials are designed to promote students' engagement in important scientific practices and their application of crosscutting themes, and their understanding of core science ideas such as those identified in the NRC *Framework*. The knowledge and experiences developed and the findings from this project may help inform the design and study of curriculum, assessment, and professional development that is aligned to the goals expressed in these documents.

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