"Starch is Very Fatty": Understanding the Logic in Undergraduate Student Conceptions about Biological Molecules

Karen E. Bledsoe
Western Oregon University

ABSTRACT

Though student understanding of the nature of matter has been studied extensively, little is known about student knowledge of the biological molecules. This study examined understanding of proteins, carbohydrates, and lipids in 25 undergraduate students in order to document logical structures within student alternative concepts. Student knowledge of the particulate nature of matter (PNM) was collected in a pre-survey. Their knowledge of the biological molecules was collected via pre- and post-surveys, embedded questions, and interviews. No relationship was found between initial PNM knowledge and knowledge of molecules at the start of the course. By the end, however, strong correlations were found between initial PNM knowledge and knowledge of molecules. Students displayed alternative ways of categorizing biomolecules, using overlapping functional categories based on perceived nutritional roles. Their underlying assumptions about molecules fell into six categories: as goes macro, so goes micro; source = substance; molecule/energy equivalence; like acts upon like; functional equivalence; functional limitation. Student alternative conceptions displayed logical structure; their conceptions "worked" in their everyday lives. However, alternative categorizations of biomolecules used by low-PNM students interfered with their ability to understand biological processes that involved these molecules: enzyme activity, photosynthesis, and DNA synthesis. Educational implications of these findings are discussed.

Correspondence concerning this manuscript should be addressed to Dr. Karen E. Bledsoe, Department of Biology, Western Oregon University, Monmouth, OR, 97331, bledsoek@wou.edu

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Introduction

The study of biochemistry is grounded in the premise that all matter is made up of particles. As students are frequently taught in middle and high school science classes, atoms are particles that form the smallest unit of an element. Atoms in turn are made up of smaller particles, and atoms can bond together to form discrete particles called molecules.

To understand many of the topics taught in a general biology series at the college level, such as metabolism, photosynthesis, and protein synthesis, students must have a solid understanding of the particulate nature of matter, and more specifically the nature of the biological molecules. Consequently, general biology texts for college students (for example, Campbell, et al., 2008; Audesirk, et al., 2011) include a unit on the structure of atoms and the biological molecules: proteins, carbohydrates, lipids, and nucleic acids.

However, the research literature describes students at all levels enter their science courses with alternative conceptions regarding atoms and molecules that are well documented in the research literature, and a portion will exit secondary level coursework still reasoning with alternate conceptions (for example, Driver, et al., 1994; Harrison & Treagust, 1996; Löfgren. & Helldén, 2009). Though the majority of students entering college have heard and use the terms "atom" and "molecule," many of these students bring with them persistent alternative conceptions regarding the particulate nature of matter. Upper-level high school students often have difficulty understanding relative scale of objects that cannot be seen with the naked eye, and have the impression that all things "microscopic" are about the same size. This failure to understand scale may be one reason why some students are certain that the nucleus of the atom contains DNA and that atoms can divide like cells (Harrison & Treagust, 1996). Students bring these concepts to college with them from their high school experience. Studies have shown that at the college level, students have difficulty thinking at the molecular level. Students may assert that matter is continuous, and may use the terms "atom," "molecule" and even "cell" interchangeably (Dreyfus & Jungworth, 1988; Coll & Taylor, 2001; Williamson, et al., 2004). Even graduate chemistry students may still have difficulty understanding conservation of matter in chemical reactions (Bodner, 1991). Poor understanding of the nature of matter has consequences in science coursework. For example, a study by Othman, Treagust, and Chandrasegaran (2008) showed that undergraduate students who held alternative views of the particulate nature of matter had difficulty understanding chemical bonding in an introductory chemistry course. It seems likely that students might experience similar consequences when learning about other molecular concepts, including processes involving the biomolecules.

While particulate nature of matter has been widely studied and documented, student understanding of the biological molecules – carbohydrates, proteins, lipids, and nucleic acids – has been sparsely examined. Health education, nutrition information, food packaging, and modern diet fads have made the public aware of biological molecules in their lives, from "low fat" or "no trans-fats" announcements on food packages to entire "low carb" food sections. However, except for genetics concept studies that include student ideas about nucleic acids, and studies that examined how students understand advanced properties of organic molecules within organic chemistry classes (for example, Schmidt, 1996; Ealy and Hermanson, 2006), little work has been done regarding student ideas about the most familiar biological molecules that students are likely to encounter in an introductory biology course and in their daily lives. Studies do exist regarding teaching methods that result in improved scores on instruments that assess student mastery of pre-determined molecular concepts (for example, Mulnix, 2003; Honey & Cox, 2003). While such studies examine teaching methods to increase learning gains, the focus is not on student conceptual understanding of the molecules in question and how students reasoned about the molecules.

This study seeks to document student ideas about the biological molecules and to understand what undergraduate students know about proteins, carbohydrates, and lipids, and how their knowledge of the nature of matter and their knowledge of molecules may interact.

Young Adult Learners and the Particulate Nature of Matter

Understanding the nature of matter is often difficult for students at all levels, since atoms and molecules are too small to experience directly even with the aid of student microscopes. Students are asked to observe macroscopic properties of matter and from those infer a microscopic model of matter made up of particles with nothing between them (Pozo & Gomez-Crespo, 2005). As far as the student is concerned, the scientific models may seem like a story and have nothing to do with "real life." Multiple studies document the development of a personal theory of matter in elementary and middle school students. Studies conducted with older students in high school and college show that these students also hold non-scientific ideas about the particulate nature of matter. For example, Novick & Nussbaum (1981) found that while the majority of high school and college students in their study accepted an even distribution of particles in gas, about 10% believed most gas particles settled to the bottom of a vessel, and 50% of university undergraduate students believed that vapor, oxygen, or "air" existed between gas molecules. Fewer than 50% of university students attributed the diffusion of gas particles to random molecular motion, and about 10% held a static model of matter for all states of matter. Löfgren & Helldén (2009) found that fewer than 20% of 16-year-old students spontaneously used a particulate theory when answering questions about the state of matter. Pozo and Gomez-Crespo (2009), in a study that included upper-division university chemistry students, found that perceptions of molecular motion are influenced by the physical appearance of materials. College students were more likely to use scientific, particulate-based models when talking about gases, which are intrinsically dynamic, than when talking about solids. Students strongly associated the visible motion of the material itself with motion of molecules. Table 1 summarizes scientific views and alternative undergraduate student views of the particulate nature of matter that have been identified in research literature.

Table 1. Scientific views and alternative views identified in undergraduate students regarding the particulate nature of matter.

Scientific Views	**Alternative views**
All matter is made up of particles, i.e. atoms and molecules.	Matter is continuous. (Novick & Nussbaum, 1981; Driver, et al., 1994; Pozo & Gomez-Crespo, 2005; Talanquer, 2006)
The particles that make up matter are constantly in motion.	If matter is made up of particles, the particles are static; or, the particles are in motion in liquids and gases but static in solids. (Driver, et al., 1994; Pozo & Gomez-Crespo, 2005)
There is nothing between the particles that make up matter.	If matter is made up of particles, air (usually continuous, non-particulate) or other continuous material is between the particles. (Novick & Nussbaum, 1981; Driver, et al., 1994; Löfgren & Helldén, 2009)
Gas particles evenly distribute themselves in a container.	Gas particles settle to the bottom of a container; the rest is filled with "air" or "nothing." (Novick & Nussbaum, 1981; Driver, et al., 1994)
As matter changes from the solid state to the gaseous state, particles move further apart.	As matter changes from the solid state to the gaseous state, the particles get bigger. (Talanquer, 2006; Talanquer, 2009)

As water evaporates, its particles move apart.	As water evaporates, the particles disappear; or, the particles get bigger; or, molecules break apart into their component atoms. (Driver, et al., 1994; Löfgren & Helldén, 2009; Talanquer, 2006; Talanquer, 2009)

Young adult learners and the Biological Molecules

While student understanding of the particulate nature of matter has been extensively studied, far less is known about student views regarding the major classes of biological molecules. However, many concepts in an introductory biology course, such as metabolism, photosynthesis, and protein synthesis, require an understanding of the nature of proteins, lipids, or carbohydrates. Studies regarding student concepts of biological processes contain suggestions that student understanding is often grounded in their reasoning about biological molecules and materials. For example, Fisher (1985) found that when asked to identify the products of DNA-to-protein translation in a multiple choice question, most undergraduate students selected "amino acid" from the choices, when "activating enzymes" was the correct answer. Almost universally, students failed to recognize enzymes as proteins and therefore the product of translation. Hazel and Prosser (1994), when examining undergraduate student concepts of photosynthesis, found that while students often knew that plants absorb carbon dioxide, seldom did they identify carbon dioxide as a carbon source to build carbohydrates.

Barak, et al. (1999), in examining high school seniors' reasoning about photosynthesis and respiration, characterized a "matter based" ontology in which processes become a "black box," into which materials go while others emerge. Students who move to a "process-based" ontology demonstrate a more meaningful level of understanding. Yet to achieve the process-based thinking, students must understand the materials involved and reason with them in a meaningful way.

This study seeks to understand student concepts regarding the biological molecules and how students reason with their understanding. Specifically, the study investigates the following:

- What relationship exists between students' understanding of the particulate nature of matter and their understanding of proteins, carbohydrates, and lipids at the start and at the end of the course?
- What relationship exists between a student's understanding of the particulate nature of matter and that student's emerging knowledge of biological molecules within the context of three biological processes: enzyme activity, photosynthesis, and protein synthesis?
- What logical structures exist in undergraduate student conceptions when reasoning about the biological molecules?

Theoretical Framework

The study was conducted from a constructivist perspective, since the purpose was to document student perceptions and explanations, in order to understand what ideas about molecules the students had constructed for themselves as they entered the course and as they engaged with the course material. Researchers generally agree that students bring their idiosyncratic collections of daily knowledge to the classroom, knowledge that is made up of their spontaneous interactions with their world (Marin, et al., 2004). Constructivism is an epistemology that embraces this idea that learners are not blank slates; rather, they construct knowledge for themselves using information gathered through the senses and filtered through the lenses of prior knowledge. Knowledge construction may take place within the individual's mind (as described by Piaget, 1977) or within a social milieu (as described by Vygotsky, 1968), but in either case, knowledge is not transferred intact and unchanged from teacher to learner. Rather, students actively construct their knowledge of the world using their own experiences and beliefs as filters (Phillips, 1995).

Controversy exists, however, about what form that prior knowledge takes and consequently how construction of concepts occurs. Out of constructivist research, two general lines of thought arose, two "flavors" of constructivism as applied to concept formation.

"Theory" theory, or misconceptions constructivism, as epitomized by Posner, Strike, Hewson, and Gertzog (1982), McClosky (1983), Samarapungavan and Wiers (1997) and others, posits that misconceptions (also described as alternate conceptions or naïve theories) exist as implicit, stable, global, and theory-like explanatory frameworks in the learner's mind. These implicit theories reflect daily experience, which is generally limited by a learner's own senses (Pozo & Gomez-Crespo, 2005). Theories are often in the form of mental models that are constructed, situated, and locally consistent (Pozo & Gomez-Crespo, 2005). Such frameworks may have an intuitive appeal, and may resemble explanatory theories from past centuries (Samarapungavan & Wiers, 1997).

Consistency within student-generated theories tends to render them resistant to conceptual change. The goal of teaching is to challenge existing alternate conceptions, such as by demonstrating discrepant events, to promote conceptual change (Posner, et al., 1982). The learner discovers that the existing alternate conception is no longer fruitful – that is, the prior conception no longer provides a satisfactory explanation – and the learner then seeks and constructs a new explanation. As learners grow dissatisfied with their old frameworks, they adopt a new framework to entirely replace the old. While new explanations may at times be constructed on the spot when learners are questioned (Strike & Posner, 1992), the learner's internalized theory remains the unit of description when analyzing student reasoning. "Confront and replace" is the primary means of conceptual change (Elby, 2000). Studies grounded in "Theory" theory lead to categorical and often hierarchical descriptions of student understanding. For example, Vosinadu and Brewer (1992; 1994) describe children's models of Earth, which have an influence on children's models of the day/night cycle. Very young children often believe that Earth is a flat rectangle, based on their everyday experiences. When told that the world is round, they may replace the model of a flat rectangle with a model of a flat disk. As children learn that Earth is a sphere, they may believe that people live on a flat disk inside, or on top of a flattened sphere. With the development of abstract thinking, learners can abandon a flat Earth model and adopt a spherical model that includes a concept of gravity, such that people can live on all surfaces of a spherical planet. Children using a flat Earth model often believe that the sun moves in relation to Earth, moving behind mountains or moving away from Earth at night. Children employing a spherical Earth model may believe the sun rotates around the sphere, or that the spherical Earth moves in space around the sun.

In contrast, the “fine grained” theory of constructivism describes learner’s knowledge as loosely connected or entirely disconnected mini-generalization, or “p-prims” (that is, phenomenological primitives, diSessa, 1993). Knowledge is generalized from experience, but exists as small, sometimes interconnection mini-generalizations: in a sense, a “particle theory” of knowledge. Learners may construct understanding on the fly, assembling mini-generalizations into an explanation that, in their view, fits the question or the data before them.

As learners interpret a phenomenon or a representation, their interpretation is often filtered, consciously or unconsciously, through one or more underlying interpretive rules, such as “More A, more B,” or “Same A, Same B” (Stavy & Tirosh, 2000; Elby, 2000). For example, a “More A, more B” rule may lead a child to believe that a solid candle will weigh more than the same candle when it is melted. The solid is assumed to be harder and stronger, and is therefore assumed to weigh more. Another underlying rule, “closer = stronger” is experienced as learners approach or move away from a heat source (Hammer & van Zee, 2006). The simple common-sense rule is applied when learners are asked to explain the seasons. It is logical to believe that the Earth warms as it moves closer to the sun, and once the rule is applied, the learner stops looking for another answer, having found one that works in that learner’s point of view (Hammer & van Zee, 2006). The underlying rule “closer = stronger” is *not* a misconception in and of itself. It is simply not the rule that scientists have discovered applies to the cause of the seasons.

In a fine-grained framework, conceptual change does not consist of replacing entire naïve models with scientific understanding. Instead, the learner alters one or more mini-generalizations within an explanation in order to achieve coherence and global consistency (Stavy & Tirosh, 2000; Elby, 2000). Where student explanations often differ from scientific explanations is in global consistency. The ultimate goal in science is to be consistent, and to develop a coherent understanding of natural phenomena. Scientific inquiry is “the pursuit of mechanistic, coherent accounts of natural phenomena.” (Hammer & van Zee, 2006, p. 27). Naïve ideas tend to be fragmented from a scientific point of view, but are often internally consistent with in a given context or within a student’s own epistemology (Chi 1992; Chi & Slotta, 1993; Pozo & Gomez-Crespo, 2005). Such apparent inconsistencies, which are not inconsistent from the learner’s point of view, may be the inevitable result of student thinking which tends to vary from context to context (Liu, 2001). One goal of classroom inquiry is to give students a range of learning opportunities in which they directly experience natural phenomena and develop evidence-based explanations for their observations.

It is from this second, fine-grained theory that the knowledge of students in this study is examined. In addition to documenting student ideas about molecules and their explanations for phenomenon on the molecular level, the study seeks to describe underlying rules from which the ideas and explanations arise. What appears to be a misconception, a student explanation at odds with a scientific explanation, may have a logical basis in which the student grounds their belief in other scientific explanations that they have learned or phenomena that they have experienced. Molecular concepts are particularly difficult for students, since the phenomena they must form concepts about cannot be directly experienced. Science itself, when describing phenomena at the molecular level, relies almost entirely on indirect evidence. Scientific laws and theories of molecular events can be thought of as stories constructed from indirect evidence (Lederman, 1998). Students, too, construct stories about molecules based on the knowledge presented in class, in the textbook, from experience in labs, and from their daily experience. Understanding logical rules or structures from which their explanations arise may be useful to educators in selecting teaching methods to address common alternative conceptions.

Talanquer (2009) designed a useful framework that describes implicit student assumptions about matter that may underlie many student misconceptions described in PNM studies. Talanquer describes five types of assumptions showing dimensions from novice to advanced: Categories, Structure, Properties, Dynamics, and Interactions. "Categories" concerns student assumptions about category membership based on the properties of matter. Novices tend to reason using surface similarities, leading them to believe that molecules move in gaseous substances (since gas as a whole moves), but not in solid substances, or that some substances are made of molecules while others are continuous (such as visually non-dynamic solids). "Structure" concerns structure of matter, which novices tend to view as continuous or as particles embedded in a matrix. Those who think of matter as continuous may believe that water molecules are made of water, while more experienced students can identify hydrogen and oxygen as components. However, even experienced students may believe that between water molecules is more water, or air, or other "stuff." "Properties" concerns thinking about the properties at the macro and micro level. Novices often assume that particles of matter are very much like a larger sample of matter: that gold atoms, for example, are shiny and yellow. "Dynamics" concerns student assumptions about kinetic molecular motion, from a model of static particles, to motion contingent on outside forces (such as the application of heat), to an understanding of motion as an intrinsic property. "Interactions" concerns student understandings of how particles interact and under what circumstances, from a belief that particles must touch to interact, to a belief that interaction requires an outside force (such as heat), to an understanding that interaction is an intrinsic property. Talanquer's framework provided a useful tool for framing pre-survey PNM items, and as a lens for analyzing the results.

Methods

Subjects

Subjects for the study were 25 adult students (ages 18 – 40) at a small west coast university, enrolled in a summer nonmajors biology course taught by the researcher. Sixteen of the students were female, nine were male. Nine students agreed to take part in clinical interviews outside of class. All students gave informed consent to use their written assignments as data for this study.

Coursework

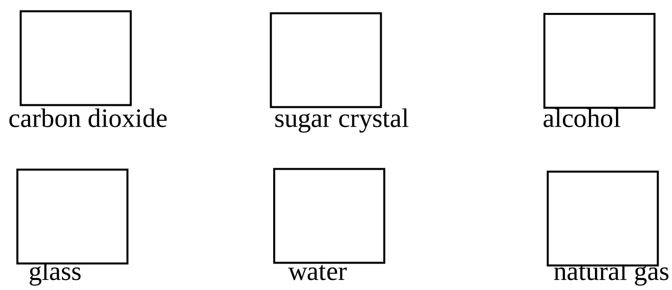
The summer session was chosen for the small class size that allowed greater interaction between the instructor and the students than the normal large lecture format during the school year, thus allowing greater opportunity for insights into student understanding and reasoning. The course format consisted of eight 2-hour labs and sixteen 2-hour lectures over a four-week period. The class met four days each week for lecture, lab, or both. The course was taught as a traditional lecture and lab class using existing curriculum materials, including eight hands-on labs that were designed by the biology faculty No special instructional interventions were devised to address student prior conceptions during the term beyond what was normally taught in the course.

Students began the term with an introduction to atoms, atomic bonding, and the biological molecules. This information served as a foundation for the units that followed. Students were encouraged to memorize a table consisting of the four classes of biological molecules (carbohydrates, proteins, lipids, nucleic acids), their monomers or subunits, the reagents used to test for them, and the enzymes that students would observe digesting three of the large polymers into their monomers.

Following the introductory unit, students studied enzyme activity, cell energetics, protein synthesis, and patterns of heredity. Understanding enzymes, cell energetics (cellular respiration and photosynthesis) and protein synthesis required an understanding of the biomolecules, and so were chosen as units in which to study emerging contextual knowledge of biomolecules. During these units, students engaged in three labs that allowed students to physically engage with the systems that they were studying. The enzyme lab involved observing racks of test tubes containing known polymers (starch, albumin protein, and cooking oil as a lipid) that had been treated with unknown enzymes (amylase, pepsin, and lipase), then tested with a reagent that tested for the known polymer. Students were to observe the results and identify each of the unknown enzymes. Students were then given a bag made of dialysis tubing and loaded with an unknown polymer (starch or albumin) that had been given one of three treatments: amylase, pepsin, or water. Students tested the contents of the bag and the water in the beaker that it was incubating in, then compared their data to the class data to identify their polymer and treatment. In the photosynthesis lab, students measured oxygen output from photosynthesizing *Elodea*, blew carbon dioxide into bromothymol blue indicator solution to see it change to yellow, then added *Elodea* and observed the reverse color change as the plant took up carbon dioxide during photosynthesis, and stained *Pelargonium* leaves to observe starch storage. In a prior lab on cell structure, students had observed amyloplasts (starch storage organelles) in potato tissue, so were already familiar with starch storage in plant cells. In the protein synthesis lab, student worked with paper models to model the processes of DNA replication, then modeled transcription and translation. Each lab ended with homework questions that were collected and copied for analysis. After lab, the instructor jotted down the content of conversations with students that the instructor could recall.

Pre-survey: On the first day of class, students were asked to complete a survey to assess their understanding of the particulate nature of matter and of the biological molecules. The particulate nature of matter survey consisted of six items, based on descriptions in Driver, et al. (1994) of student ideas about matter and survey items used to assess these ideas. The choice of questions is further grounded in Talanquer's (2009) work on implicit student assumptions about matter, already described in the theoretical framework. Table 2 lists the questions in the order they appeared on the survey and shows the relationship between the survey items and Talanquer's framework. Each student's survey was assessed in light of Talanquer's framework. Questions were clustered within each of the five assumptions. While analysis was primarily qualitative, each student's apparent alignment with the dimensions scored on a 0 to 3 scale as a means of roughly quantifying the novice to expert scale for the sake of comparison: 0 if left blank or answered with "I don't know," 1 for alignment with novice, 3 for alignment with expert, and 2 for answers falling between the two on dimensions where this was included.

Table 2. Relationship between survey items and Talanquer's (2009) implicit student assumptions about the particulate nature of matter, from novice to advanced.

Type	**Dimension (novice to advanced)**	**Survey items**
Categories	surface similarity to structural similarity	Imagine the squares below are closed containers filled with the six substances labeled. Imagine also that you have a machine that can magnify each substance until you can see the molecules it is made of. Using small circles to represent molecules, sketch which materials are made of molecules, where molecules would be in the containers, and relatively how far apart they would be. Assume all substances are at room temperature. 
Structure	Continuous to embedded granularity to particles in a vacuum	In any of these substances [in the sketches above], is there anything between the molecules? Explain. What are water molecules made of? Sketch your best understanding of a water molecule. Sketch your best understanding of the structure of an atom.
Dynamics	Static to Contingent dynamic to Intrinsic dynamic	In any of these substances [in the sketches above], do the molecules move? Explain.
Properties	Inheritance to Emergence	Two students watch a piece of dry ice (solid carbon dioxide) shrink as the solid turns to carbon dioxide gas. The students try to explain what they have observed. Which student's statement do you agree with most, and why? - "The carbon dioxide molecules move further apart from one another as it becomes gas." - "The carbon dioxide molecules expand and get bigger as it becomes gas."
Interactions	Contact-interactive to Contingent-interactive to Intrinsic-Interactive	Element A and Element B, when put in the same container, chemically bond to form Compound C. Both elements, in normal classroom conditions, can be heated or cooled to make them solids, liquids, or gases. Suppose a student combines the two elements when both are in the gaseous, then liquid, then solid state. Will the atoms of Element A and Element B form bonds when the elements are in: - a gaseous state? (Yes / No) - a liquid state? (Yes / No) - a solid state? (Yes / No) Explain your responses.

In addition, students completed a series of open-ended questions developed by the researcher were presented on the overhead projector to estimate their prior knowledge of proteins, lipids, and carbohydrates. The slides showed images of familiar products such as corn starch, sugar, and vegetable oil, and included these questions:

- "Do humans need to eat proteins? Why or why not?" This question allowed students to begin in familiar territory. Their ideas about the nutritional function of biomolecules was expected to reveal underlying assumptions about the nature of the same biomolecules.
- "Please name some specific proteins that you are aware of." This question, based on informal assessments of students in other courses, was expected to determine whether students held a nutritional concept of "protein" as a single substance, and a biomolecular concept of "proteins" as distinct types within a category. It was also included to give some idea of each student's categorization of biomolecules.
- "At the molecular level, what are proteins made of?" This question moves to less familiar territory, where students are asked to think about biomolecules at the particulate level.
- "What else do you know about proteins?" This open-ended question was included to allow students to express ideas that did not fit into the prior three questions.

The same set of questions was repeated for carbohydrates and fats. The question set used vocabulary familiar to the students; hence the use of the word "fat" rather than "lipid." Use of nutritional aspects of the molecules was intended as familiar beginning for discussion, and was expected up front to elicit health-related and macro-level responses. However, grounding the questions in a familiar context is useful, as it gives students a starting point in their own prior knowledge (Hammer & van Zee, 2006) before moving to the less familiar, micro level. Students wrote their responses on their own paper and their papers were collected for analysis. The question matrix provided a starting point for discussion during interviews.

Post-survey: The same molecule question that was used as a pre-survey set was administered again at the end of the term with the final exam as one measure of changes in student concepts. The responses were assessed qualitatively for content. In addition, the questions were scored quantitatively on a 0-3 scale. Students were scored 0 if they gave no response, 1 if they demonstrated alternate conceptions, 2 if their answer included both alternate and scientific conceptions, and 3 if their response indicated scientific knowledge.

Interviews: One shortcoming of paper-and-pencil tasks is that they are too similar to exams to fully capture student knowledge. Students may treat instruments as they would exams, attempting to "mind read" by writing down their closest estimate of the instructor's view of correct answer instead of expressing their own understanding (Marin, et al., 2004). Or students may memorize and respond with phrases and expressions that are appropriate but that the student does not fully comprehend (Williamson & Abraham, 1995). In addition, the wording of written questions can affect student responses. Questions that include the words "atom" or "molecule" cue students that a micro-level answer is desired, even if the student would not have spontaneously responded on the micro level (Williamson et al, 2004). Therefore interviews were used to capture a deeper understanding of student views.

Nine students volunteered to be interviewed at the beginning and at the end of the term, using a clinical interview format. Each student was first asked to describe what they knew about proteins, carbohydrates, and fats. If they had nothing to say, students were asked what they recalled from class and from nutritional packaging that they had seen as familiar starting points. Following that, they were presented with their completed pre-survey and asked to read their response aloud, then elaborate on their responses. At the end-of-term interviews, students were asked to discuss whether their ideas had changed since the pre-survey. Interviews were audio-recorded for later analysis.

Embedded questions: Throughout the course, students responded in-class daily work questions and lab homework that were part of the course material written by the faculty. From this body of work, questions related to biological molecules were collected for analysis. Questions specifically designed to capture student understanding of the role of biological molecules were included in written summaries administered at the end of three labs: a lab on enzyme activity, a photosynthesis lab, and a lab on protein synthesis. Model responses to embedded questions were created by the researcher and used in class discussions when the responses were handed back. Written responses were analyzed qualitatively for content. As a means to roughly quantify the responses for additional comparison, student responses were scored on a 1-3 scale, where 3 indicated a scientific understanding, 2 a partial understanding and some alternate explanations, and 1 indicated alternate explanations. A score of 0 was given for no response. Examples of embedded questions are listed in Table 3.

Table 3: Examples of embedded questions used to assess student molecular knowledge in the context of units on molecules, photosynthesis, and protein synthesis. Questions relate directly to lab activities.

Unit	Delivery	Questions
Biological molecules	End of Biological Molecules lab	A student learns that starch is a chain of glucose (sugar) molecules linked together, and that proteins are chains of amino acids linked together. The student knows that Benedict's reagent tests for glucose, and that Ninhydrin reagent tests for amino acids. a. If the student tests starch with Benedict's, will the student get a positive or a negative test? Explain. b. If the student tests albumin protein with Ninhydrin, will the student get a positive or a negative test? Why?
	In-class daily work (following Enzymes lab)	If you tested the following mixtures for starch, sugar, protein, and amino acids, what would you find? a. starch + amylase b. starch + pepsin c. protein + amylase d. protein + pepsin
Photosynthesis	End of photosynthesis lab	Plants take in carbon dioxide during photosynthesis. What is the carbon dioxide used for? What is the final product of photosynthesis? What is it used for?
	In-class daily work	From tiny acorns, a mighty oak grows. The wood that makes up the tree wasn't all packed in the acorn. Where did the raw material to make the

		wood come from?
Protein synthesis	End of protein synthesis lab	DNA polymerase is an important molecule in DNA transcription. a. What kind of molecule is DNA polymerase? b. What smaller monomer(s) is DNA polymerase made of? c. How is DNA polymerase itself made?
	In-class daily work	Helicase is an enzyme. To which class of molecules do enzymes belong? Where are the instructions for making helicase found?

Data analysis

All recordings and written responses from summer term were transcribed. Data were entered into TAMS Analyzer 3.44 qualitative data analysis software (Weinstein, 2008) for analysis. The first passes through the data identified student references to carbohydrates, proteins, lipids, and to atoms and molecules in general. Each reference was tagged with labels related to student views regarding the molecules. For example, tags for student views of carbohydrates included "carbs-supply_energy," "carbs-are_sugar," "carbs-unnecessary," "carbs-contain_fat," among other student ideas.

Further passes through the data grouped the tags into larger categories that expressed similar ideas. Categories that emerged at this stage included judgment statements about the substances (such as "good for you"), statements regarding the molecular structure (such as, "protein made of amino acids" or "sugar contains fat"), and how the substances are used in the body (such as "protein gives energy"). Since the author was working alone, conversations and interviews with students provided member checks wherever possible to test categories of knowledge and guard against bias during this process of initial analysis.

Final passes consisted of a search for unifying assumptions underlying alternative conceptions. The term had ended by the time of the final analysis, but where possible, some member checks could be obtained by email with participating students for some of the data as a test of the final categories. The unifying assumptions crossed boundaries between the scientific categories of proteins, carbohydrates, and lipids. For example alternative ideas appeared that the molecules themselves resembled their macro-level appearance or perceived macro-level function: that protein molecules were "strong" like muscles, or that fat molecules were round and bouncy. This "as goes macro, so goes micro" assumption, where it appeared in student descriptions, was used by those students to describe all three categories of biological molecules and consequently was interpreted as an underlying assumption. Similarly, students were identified who consistently assumed that an enzyme that worked on a particular substrate (such as a lipase that broke down a lipid or DNA helicase that unzips DNA) were themselves composed of that substrate. This suggested and underlying assumption of functional equivalence: that like acts upon like.

Finally, student data were compared with Talanquer's (2006) explanatory framework of student reasoning. The framework was designed around student reasoning with the particulate nature of matter. The categories provided insight into understanding how students thought about molecules in the contexts in which they were presented during lecture and lab.

Results and Discussion

This section will begin with a fine-grained description of knowledge expressed by students regarding the particulate nature of matter, biological molecules, and interactions between those bodies of knowledge at the start and at the end of the course. Following this will be a discussion of the bigger picture, so to speak: the underlying assumptions behind student knowledge, and the logic underlying student alternative concepts around biological molecules that were expressed in this group of students. The research questions are addressed at the end of this section.

At the beginning of the term, all students had at least heard the terms "protein," "carbohydrate," and "fat." Their knowledge, however, included a wide range of scientific and alternate concepts. As interviewed students related their ides, they noted that they drew on learning from prior biology and health courses, exposure to public media, and ideas acquired through social relationships. Ideas ranged from no expressed concept of atomic or molecular structure to detailed accounts of the sub-components of large polymers. This section will describe student knowledge of the particulate nature of matter, their knowledge of biological molecules, and relationships uncovered between the two sets of knowledge at the beginning of the term. The relationship between student knowledge of the nature of matter and changes in their knowledge of biological molecules during the term will also be discussed.

Initial understanding of the particulate nature of matter

PNM survey scores at the start of the term divided the students into two distinct, non-overlapping groups. Out of a possible score of 15, fourteen of the 25 students scored between 0 and 8, while the remaining 11 students scored between 11 and 14. The first group was labeled the low-PNM group, and the second the high-PNM group.

Overall, students showed the highest scientific knowledge on the "properties" scale (class mean = 2.12 on a scale of 0 to 3), where majority of students (20 out of 25) answering the "properties" question agreed with a statement that molecules move apart as carbon dioxide sublimates from its solid state to a gaseous state. Seven students gave an appropriate explanation such as, "Because molecules don't get bigger, gas molecules just are further apart from each other than in solids." Twelve of the students chose the appropriate statement, but provided no explanation or offered an explanation that described the scenario but did not explain it, such as, "Because as it becomes a gas it unites with the air above it."

Students employed more alternative explanations on the other four scales, which were also scored from 0 to 3. On "interactions" (class mean = 1.75), only four students expressed an intrinsic interactive belief, that molecules can interact in any of the three states. Twelve expressed a contingent-interactive belief, stating that molecules can interact in some states, but not in others, believing either that gas particles cannot interact because they are too far apart, or that solids cannot interact because the particles in solids do not move. On "categories" (class mean = 1.54), all of the high PNM students provided a depiction of different substances as particles, with particles of gas further apart and particles of a solid close together, and created similar depictions for substances in the same state of matter. Only one of the low-PNM students provided such a depiction. The rest wrote question marks or did not answer. Interviewed students in this group could not provide a verbal response even after the question was explained, suggesting that it was lack of knowledge rather than lack of question clarity that resulted in no response. On “dynamics,” (class mean = 1.29), one student believed that particles are in motion in all states of matter. Fourteen believed particles are only in motion in gasses, liquids, or both, while the remaining students did not know if particles move. One belief expressed was that only “natural” particles move: “Yes; water, natural gas & carbon dioxide move because they are natural elements.” The class scored lowest of all on “structures” (class mean = 1.29). Six students, all of the high-PNM, described atoms and molecules in terms of particles in a vacuum, with nothing between. Six more described particles embedded in a matrix, such as, “In the gases yes their [sic] is air between them,” and, “I would guess there is cytoplasm between them,” the latter suggesting a confusion between molecules and cells, a confusion seen in other students during the term. The remaining students could not provide an answer.

The initial interviews revealed further details of student ideas of the particulate nature of matter. Of the students who volunteered for the interview, four were in the high-PNM group and five in the low-PNM group. During the interview, students discussed their responses and were asked to sketch an atom and talk about it.

Kim, a low-PNM student, exemplified one of the difficulties encountered by other low-PNM students when discussing matter. During the interview she drew concentric rings to depict her idea of both atoms and molecules. The atom diagram had line radiating out from it. Kim explained her diagram as follows:

> Kim: Um, there’s a nucleus. And then there’s branches, that bond part of the atom together.
> Interviewer: Okay, so the bonding, what’s being bonded here?
> Kim: Um, the DNA in the atom.
> Interviewer: Okay, so there’s DNA in an atom?
> Kim: Um hm. (Nodding)
> Interviewer: Okay. And then these look pretty similar (pointing to sketches of molecules). Is that how you picture molecules?
> Kim: Um, yeah, I just picture this one (pointing to her sketch of a fat molecule) having logs more, like rings or branches, however it looks, just because it’s, probably going to be bigger if it’s fatty. At least that’s what I think.
> Interviewer: Okay, so is there a difference between molecules and atoms?
> Kim: Um, molecules are enzymes. Um, yeah, they both are, um, everything has DNA, so there’s a nucleus, I think.

Kim’s puzzlement over the atomic structure, including placing DNA in the nucleus of an atom, reflected an understanding of micro-level objects that differed from a scientific understanding in which atoms make up molecules and therefore are generally smaller than molecules. For Kim, any one of these classes of objects could be just about any size relative to one another. Nor was she certain at this point that molecules were composed of atoms. Thus she saw no difficulty in believing that an atom could have DNA molecules inside of it. Atoms, molecules, and cells were all microscopic particles that Kim did not distinguish by scale; essentially, everything microscopic was about the same size. Kim’s views, which were expressed by other students at the start of and during the term, are consistent with the findings of Dreyfus & Jungworth (1988), in which students with naïve views of matter often fail to recognize differences of scale on the micro-level. Consequently, students may use the terms "atom," "molecule," and "cell" interchangeably when describing any microscopic object.

Overall, the results of the PNM survey are consistent with earlier studies on student beliefs about the nature of matter. Novick & Nussbaum (1981) for example, as noted earlier, found that about half of undergraduate students believed that "air" existed between air molecules. Similarly, half of the students in this study arrived at the university with low knowledge of the nature of matter, and even those categorized as high-PNM expressed alternate beliefs about matter. All of these students had experienced other science courses at some point in their lives, whether other college courses or in high school, and had learned various aspects of the nature of matter. After analyzing the PNM survey, the results were compared with their understanding of biological molecules to determine if a relationship between the two existed.

Initial understanding of biological molecules

As with atoms and molecules, most students had a least heard the terms "protein," "carbohydrate," and "fat," though they were less familiar with "lipid." Hence "fat" was the term used on the pre-survey and in the initial interviews. Their knowledge, however, was notably sparse and superficial.

Proteins: All students indicated on the pre-survey that proteins were essential nutrients. Students stated that proteins were used for "fuel" or "energy" (7 students), or to build, support, or strengthen muscles (8 students). Other students held less precise notions that proteins "help the functions of the Body," or, "helps maintain healthy body and tissues." When asked to name specific proteins, 11 out of 25 students left the question blank. Ten students answered with nutritional sources of proteins, such as meat and milk. Two students responded with "enzymes," and one with "hemoglobin." Ten students named "amino acids" when asked what proteins were made of, an idea recalled from instruction in other science classes. This was the only expressed idea about the structural aspects of proteins.

The strong conceptual association between proteins and energy caused some initial confusion when categorizing proteins within the biological molecules. One of the interviewed students, Tasha (high-PNM), tentatively categorized proteins as a kind of carbohydrate, reasoning that if both proteins and carbohydrates were energy sources, then protein must be a carbohydrate, though she was not entirely satisfied with her conclusion.

Carbohydrates: Student ideas about carbohydrates were strongly judgmental, tending to divide carbohydrates into "good" and "bad" categories. "Good" carbohydrates were associated with whole grains, vegetables, and fruit, while "bad" carbohydrates were associated with candy and processed foods, and described in terms of "cheap fillers" and "empty calories." Half of the students associated carbohydrates with energy or fuel for the body. Their language was couched in both terms of carbohydrates *providing* energy and carbohydrates being a *form* of energy, suggesting a material conception of energy. This equivalence between energy and material has been noted in other content areas, including electrical concepts (for example, Bledsoe, 2007) and physics (for example, Watts, 1983), so it was not surprising to find a similar view in the context of food energy as well. When asked to name specific carbohydrates, nine students named nutritional sources, such as bread, pasta, or potatoes. Three listed “sugar” and two named “starch.” When asked what carbohydrates were made of, six stated “sugars.”

Seven students initially equated carbohydrates, especially sugars, with fats, using phrases such as “Carbs are foods that are high in fat,” and “Low carb means low fat.” These students all listed foods associated with high fat content as sources of carbohydrates: junk food, pizza, and chips. Julie (low-PNM), on both her final interview and post-survey, described carbohydrates as “fatty.” In some phrases, students stated definitively that sugar contained fats; at other times, students seemed to be using “fat” and “calorie” as equivalent terms, though there was not enough data to get a fix on the nature of this association.

Lipids: Students were almost universally negative about lipids in their pre-surveys. Two students believed that humans do not need to eat fats. Twelve students associated fats with processed and “junk” foods. Six students mentioned candy as a source of fat, supporting a mental equivalency between fat and sugar seen in the responses about carbohydrates. In describing the function of fats, half of the students identified fat as an energy source, again viewing fats and carbohydrates as nutritionally equivalent.

When asked to name specific fats, once again students who responded listed nutritional sources, suggesting a mental equivalence between the substance and its source. Six students listed butter, bacon, or junk food as types of fats. Four listed “sugar” or “starch” as fats. One student listed “water” and one believed that “salt” was a fat, conceptually linking the high fat content and high sodium content of “junk” foods.

As expected, given the nature of the questions on the pre-survey, their expressed knowledge was largely nutritional. However, even in interviews when asked about the biological molecules themselves, students knew very little beyond nutritional information, and even their nutritional understanding was highly limited, often to single generalized roles for each of the different molecules. Their nutritional knowledge influenced the ways in which students categorized the biological molecules, mentally arranging them by perceived function or by how “good” or “bad” they were for human health. Rarely was any mention made of molecules or any other type of particulate structure, beyond an expressed belief that proteins were made of amino acids and carbohydrates made of sugars. When asked to draw these molecules, half of the students had no idea and left the question blank. Of those who answered, seven drew diagrams that resembled their diagrams of atoms, only larger and with more rings, or with lines connecting the electrons, recollecting diagrams showing bonds between atoms. Two students drew illustrations that reflected their ideas about the macro-level nature of the substances. Tasha, for example, drew round forms for fat molecules and wrote that they were “round and bouncy,” like fat. Stan drew a muscle man for a protein molecule, explaining verbally that protein molecules must be “strong” because muscles were strong. This micro/macro equivalence has been noted in studies on the particulate nature of matter (for example, Talanquer, 2009).

Relationship between student PNM knowledge and initial understanding of biological molecules

Molecular knowledge data from the pre-surveys was scored and the scores compared with student knowledge of the particulate nature of matter using a Spearman Rank Order Correlation test. While this study is a qualitative descriptive study, some numerical description of relationships between constructs was desired. Within the obvious constraints of a small sample size and nonparametric data within the specific context of the study, no significant correlation was found within this group between student knowledge of the particulate nature of matter and their initial knowledge of biological molecules ($r = 0.022$, $p = 0.91$). Given the overall limited nature of knowledge observed in these students in both areas, the lack of correlation is not surprising. While students knew something about atoms and molecules, both high-PNM and low-PNM students had very little knowledge of specific classes of biological molecules. What knowledge they did express was superficial and idiosyncratic, or non-existent in some cases.

In the initial interviews, most of the student talk was about these substances at the macro level, in terms of human nutrition. When encouraged to talk about proteins, carbohydrates, and lipids at a molecular level, students had very little to offer. The most common recollection concerning molecular structure was that proteins were made of amino acids, and while this was by no means universal, it did indicate some knowledge that proteins are structures made of smaller structures. Students associated "carbohydrate" with "sugar," but there the association was less certain. No students suggested that complex carbohydrates were composed of sugars in the way that they believed proteins were made of amino acids. Rather, the two were seen as simply different members of the class "carbohydrate." As with the written surveys, no relationship could be discerned between knowledge of the nature of matter and knowledge of biological molecules, but again, this may simply be because their knowledge of biological molecules was so small.

It was evident, however, that some students understood the particulate nature of matter better than others when the course began. Both groups of students were assessed during the term to determine if a relationship existed between their understanding of the nature of matter and their developing understanding of biological molecules in the context of enzyme activity, photosynthesis, and protein synthesis, three topics that require an understanding of the nature of the molecules involved in order to master.

Emerging contextual student understanding of biological molecules

As students engaged in lab and class activities regarding enzymes, cell energetics, and protein synthesis, their responses to conceptual questions embedded in their homework or delivered as in-class Daily Work questions were collected. Of interest was capturing their ideas about biological molecules in the context of these biological systems.

Enzyme activity: The enzyme lab was a difficult lab for students as it required synthesizing their knowledge of polymers, monomers, the reagents that test for the substances, and the enzymes that break each polymer into its monomer. Students frequently had to refer to a table that outlined these relationships as they attempted to reason their way through the puzzles of identifying the unknowns. Following the lab, as part of their homework, students were given a written task that described four combinations of polymers and enzymes that they had encountered in lab: starch and amylase, starch and pepsin, protein and amylase, and protein and pepsin. They were to state what they would find if they tested each mixture, assuming that the enzyme had sufficient time to completely digest the polymer. This was designed as a near-transfer question, asking students to apply their observations from lab. Twenty-four students completed this question.

Overall, the majority of students provided an answer that resembled their findings from lab. For the starch/amylase mixture, 19 of the 24 students stated that amylase would break starch into its monomer, glucose. Three more simply wrote “positive,” and stated verbally that their answer meant that they believed that amylase would break down starch: that the mixture would test “positive” for enzyme activity. One student wrote “amylase,” stating verbally that if it were present, it should “give a positive test,” while another wrote “proteins, amino acids,” but could not give a specific reason.

For the protein/pepsin mixture, results were similar. Twenty-two students either identified amino acids as the product, or wrote in some form the idea that pepsin would break protein apart into its monomer. Two students did not answer the question.

For the starch/pepsin mixture, where there was a mismatch between polymer and enzyme, students had only slightly more difficulty. Four students explicitly stated that the mixture would test positive for starch. Of the remaining students, 17 wrote “nothing,” or “no reaction.” Four who were questioned informally stated that they mean that pepsin would not interact with starch. They had been thinking only in terms of the interaction and had overlooked the fact that starch would still be present to give a positive test. One student wrote “simple sugars,” associating the presence of starch and an enzyme the release of sugars, indicating an understanding that starch was composed of sugars. Another wrote “fatty acids,” expressing a belief that starch contained fats.

For the other mismatched pair, the protein/amylase mixture, results were similar. Two students explicitly stated that they the mixture would test positive for proteins. Seventeen wrote “no reaction” or “nothing,” again indicating their belief that the enzyme would not break down the polymer. One student thought that amino acids should be present because an enzyme was present, associating proteins with amino acids but not the enzyme with its substrate. One student wrote that starch would be present, stating later that she thought that amylase was a kind of carbohydrate. This association between the enzyme and its substrate came up often during student discussions in lab, and students often had to refer to their molecular table as they grappled with the idea. The remaining students left the question blank.

In the final interviews, seven of the nine students interviewed spontaneously recalled enzymes during their discussions. Corey (low-PNM), while trying to recall learned knowledge about fat molecules, said, “Um, isn’t fat, like, doesn’t it have like lipase and that sort of thing?” When asked about lipase, she could not recall what it was. Tasha (high-PNM), Kim (low-PNM) and Lorenzo (low-PNM) all spontaneously recalled that enzymes are proteins. Lorenzo specifically named DNA polymerase, from the DNA lab, as an enzyme. Seth (low-PNM) identified enzymes as substances that break down proteins. Jamal and Ami (both high-PNM) stated that enzymes were proteins and gave a specific function: that humans needed enzymes to break down substances.

The results suggested that after instruction, most students believed that starch and protein, both large molecules, were composed of smaller molecules. Other substances, enzymes, could break the larger molecules into smaller ones. What students seemed to recall most frequently was that proteins were large molecules composed of amino acids, that starch was a large molecule composed of sugars, and that enzymes were proteins that broke down other polymers. Few alternative conceptions were uncovered, suggesting few conceptual barriers to developing associations between the large polymers and their monomers in the context of enzyme activity.

Photosynthesis: Understanding photosynthesis required recognition of the same biomolecules that students had been studying, but in the context of molecular synthesis in the chloroplast. Students had to recognize the functional roles of proteins (such as proteins in the electron transport chain) and the structural nature of the final products of photosynthesis. Following the lab activities, students were asked to explain why plants take in carbon dioxide, and to identify the products of photosynthesis. While the latter was a recall question, the former asked students to make meaning of their observations during lab. Twenty-four students answered the questions. Out of the 24 responses, nine students (7 high-PNM, 2 low-PNM) stated that carbon dioxide was used to make carbon compounds, identifying the product as sugar, starch, or G3P (glyceraldehyde 3-phosphate, which had been named in lecture). One of the low-PNM students stated that carbon dioxide was "needed for the C3 cycle." The most common alternate response was an association between carbon dioxide and either food or energy for the plant. Two students (one high-PNM, one low-PNM) gave "food" as a response. Seven students (four high-PNM, three low-PNM) students gave "energy," "to make energy," "to fuel the process," or "as activating energy," as a response, even though photosynthesis had been presented as an endergonic activity, and carbon dioxide had been identified in lab and lecture as the raw material for making carbon compounds. Two low-PNM students associated carbon dioxide intake with oxygen output, stating "combines with water to make oxygen" and "CO_2 pushes out O_2." These responses may have reflected two alternate conceptions that have been noted the research literature (Driver et. al, 1994): that photosynthesis makes energy, and that the primary function of photosynthesis is to produce oxygen. They may also reflect a lack of understanding that the carbon in carbon dioxide is the same carbon in organic compounds: that carbon atoms are still carbon atoms.

The latter was supported by student responses to a variation of the well-known "where does wood come from?" question (Schneps & Sadler, 1989). Students were told that a large oak tree grew from a small acorn, and were to identify the source of raw material that the tree used to create wood. Two high-PNM students connected this question with the "why do plants take in carbon dioxide" question, stating that the raw material for making wood was carbon dioxide and even asking during the assessment, "Isn't this pretty much the same question?" This correlates with studies by Eisen and Stavy (1988) and Hazel and Prosser (1994) who found that very few students connected carbon dioxide absorption to carbohydrate production. However, seven other students (five high-PNM, two low-PNM) identified either carbon compounds (primarily glucose and starch) as materials for making wood, or the process of photosynthesis as the means for making wood, demonstrating a learned connection between photosynthesis and tissue building in plants, and a recognition that molecules produced in photosynthesis are the same molecules that make up cells and cell structures. Two low-PNM students stated that the sun was the source of wood, suggesting a material/energy equivalence. Other alternate answers included "an enzyme," "cellular respiration," "water," and for one student, "acorns." Interestingly, none of the students expressed a belief that wood was made from minerals or other solid materials taken from the soil, a belief found elsewhere in the literature, even among college graduates (Driver et. al, 1994).

In the final interviews, two of the nine interviewed students explicitly referred to photosynthesis and carbohydrate formation. Tasha (high-PNM) recalled, in describing what she knew about carbohydrates, "Well, first I think of chains of sugar, but then I think air! That's right! CO_2. That's where carbon comes from during photosynthesis."

These data indicate that the target concept – that carbon dioxide is the source of carbon for making organic compounds – was more difficult for students than the association between polymers and their monomers. In part this may be due to different lab experiences. Students handled samples of the polymers and used reagents to test for polymers and monomers, which lent some concreteness to their experience. In the photosynthesis lab, students blew carbon dioxide into an indicator solution, then watched the color return after they put in a plant and waited for some time. From these observations they had to reach a conclusion that the plant had absorbed the carbon dioxide, then connect these observations to detection of starch in a leaf by means of a familiar reagent and form the conclusion that the plant used carbon dioxide to make the carbon-based molecule, starch. This required more abstract thinking, and required recall of the knowledge that atoms bond together to make molecules.

Protein synthesis: As students learned how DNA codes for proteins, they formed an association between DNA and proteins – to the point that some students confused the two molecules. After the lab on protein synthesis, students were asked to categorize DNA polymerase within the four classes of biological molecules, and to name the monomers of DNA polymerase. Ten out of eleven high-PNM students and five out of thirteen low-PNM students who were present identified DNA polymerase as an enzyme, a protein, or both. Alternate answers included, "ribosome," "A-T," "promoter-terminator," or, "nucleic acid." Ten of the students who identified DNA polymerase as a protein also indentified its monomer as "amino acids." The remaining students stated that its monomer was "nucleotides" or a specific nucleic acid such as tRNA. While students tended to recall that the *–ase* ending signified an enzyme, and that enzymes were proteins, the "DNA" in the name "DNA polymerase" was a source of confusion for them. In-lab conversation with two of the low-PNM students revealed that these students associated DNA with DNA polymerase not only because of then name, but because the enzyme affected DNA, a conflation between enzyme and substrate that had also been noted as students worked on the enzyme lab.

However, conflating protein and DNA was not limited to one confusingly-named enzyme. A later in-class question asked students to name the monomers of DNA. Twenty-four students answered the question, and half of them (six high-PNM students, six low-PNM students) named "nucleotides" or "nucleic acids" as the monomers of DNA, indicating some difficulty in recalling which term referred to the monomer and which to the polymer while still associating both terms with the class of molecules to which DNA belongs. Four high-PNM students and five low-PNM students named "amino acids," and two low-PNM students named "proteins" as the monomers of DNA. One high-PNM student gave "DNA polymerase" as a response. Students associated DNA with protein production, but seemed unclear where amino acids for the process were coming from. Knowing that DNA contains the code for proteins seemed to give rise to the idea that DNA contained the ingredients for proteins: the amino acids.

Another in-class question asked students to identify where the code for making histone proteins (those proteins associated with chromosomes) was found. All but three of the thirteen high-PNM students who were present identified a nucleic acid, either DNA or RNA, as the molecule containing the code. Of the ten low-PNM students present, two mentioned RNA and one mentioned genes. Four left the question blank. The remaining students gave a variety of alternate answers or outright guesses: "amino acid," "prophase," "centromere," "in a specific enzyme." Several low-PNM students found the question confusing and asked for clarification during the assessment. Even when the instructor emphasized that the question asked about a kind of *protein*, they had difficulty associating with previous instruction that DNA contained the code for proteins. It became apparent during these brief conversations that the students associated DNA with the synthesis of protein as a general substance or protein as a nutrient, but not with specific named proteins. This suggested that a persistent, alternative conception existed for the term *protein*, singular, as a nutritional substance that was separate from specific *proteins*, plural, such as histone proteins or enzymes. This finding agrees with Fisher (1985), who found that students had difficulty identifying a named enzyme as a product of protein synthesis.

In the final interview, four of the nine interviewed students referred to DNA and protein synthesis when asked to recall what they knew about proteins. Kasey (low-PNM) recalled that proteins were chains of amino acids. She associated proteins with structures involved in transcription and translation, though she was unsure of the connection: "Oh, ribosomes process proteins, they help with the DNA – er, they process the proteins for cell functioning and the DNA replication, that kind of thing." Lorenzo, also a low-PNM student, listed DNA polymerase among the proteins that he could recall, stating specifically, "…the proteins basically are enzymes, you have your lysosomes with the enzymes, your DNA polymerase is an enzyme, and those should be considered a protein itself."

Ami (high-PNM) explicitly connected DNA with the formation of amino acid chains, though her verbal recall of the process was vague:

> Ami: Well, I don't always just think of protein now as just food and meat. That's not, for me I feel like that's what I've gained from this class. It's like one of the things we've covered recently is the DNA and there's amino acids which are being now like, it's protein and stuff, or it correlates with protein. So it's kind of like it's not just food it's in DNA and RNA and stuff like that, that's my understanding now. Protein is a polymer made up of monomers of amino acids and it, um, it helps with energy and stuff, still, so like I still believe that, but I don't know.
>
> Interviewer: Okay. And so what does DNA have to do with protein that you're talking about?
>
> Ami: Well, it gets replicated into like you know mRNA and then like the mRNA like we briefly talked about it on the test or like the quiz today, but it's more like through that whole process mRNA, tRNA, rRNA like ribosomal RNA makes like this amino acid chain which makes like this protein that was what I got from the chapters and stuff.

While it was unclear from this verbal expression whether she understood the details of protein synthesis, it was clear that she felt that the construction of amino acid chains was the essential process in making proteins.

What did seem clear in these data was that students needed to understand that proteins and nucleic acids were different, distinct molecules in order to understand protein synthesis. Furthermore, to understand the significance of genetic coding, students needed to distinguish *proteins* as many, distinct molecules within their molecular class, as opposed to *protein* as a single substance.

Relationship between student PNM knowledge and their emerging understanding of biological molecules.

A total of twelve individual embedded questions relating to enzymes, photosynthesis, and protein synthesis were scored on a numerical scale described above. Scores were totaled for each student as an overall estimate of their emerging understanding of biological molecules in the context of the course activities. The highest possible score was 36. The emergent understanding score was compared with student scores on the particulate nature of matter scale. A Spearman Rank Order Correlation test indicated a strong correlation between the two scales ($r = 0.54$, $p = 0.008$).

In general, students who began the term with a high understanding of the particulate nature of matter tended to respond with answers at the molecular level without prompting. Unless the question asked specifically for a molecule (such as questions asking about the monomer of a specific polymer), low-PNM students had a general tendency to give either macro-level answers, or answers that were vague or irrelevant, or left the question blank.

While learning about photosynthesis, more high-PNM students than low-PNM students were able to conceptually connect the carbon in carbon-dioxide that a plant absorbs with the carbon in organic compounds that it produces by photosynthesis. Low-PNM students tended to ascribe other functions to carbon dioxide, associating it with oxygen output or identifying it as a food source. A nutritional mode of thinking may have led these students to believe that carbon dioxide was “food” for plants: that is, something that is ingested. Belief that food is a primary source of energy may underlie the student belief that sunlight is “food” for plants. As Eisen and Stavy (1988) noted, learners often know and fixate on a few details of photosynthesis without developing a meaningful overview. About half of the low-PNM students tended to fixate on one or two ideas about photosynthesis – plants “make” oxygen or plants get their energy from the sun – and did not assimilate a model of photosynthesis as a molecule-synthesizing process.

Of course, no one question was answered universally correctly or incorrectly by either the high-PNM or low-PNM students. While a better understanding of the nature of matter seemed to increase the likelihood that a student would develop conceptual understanding of biological processes at the molecular level, it was not a guarantee. For example, in response to the question asking what plants do with carbon dioxide, seven of the twelve high-PNM students who responded gave a response that aligned with the material as taught (responses that associated carbon dioxide with organic molecule synthesis), the other five high-PNM students gave alternate responses having to do with making energy. Even at the superficial level at which it was taught in this introductory biology course, photosynthesis is a difficult subject for all students.

Protein synthesis was difficult for all students. Both high-PNM and low-PNM students showed occasions where they conflated protein and DNA, stating that DNA was made up of amino acids or that DNA polymerase was made up of nucleotides. Here again, a disconnect between "protein" and "enzyme" appeared to contribute to the difficulties students had in understanding the nature of enzymes involved in DNA synthesis and protein synthesis. However, the names of some enzymes seemed to be a contributing factor. In learning about DNA polymerase, students sometimes focused on the "DNA" in the name rather than on the *–ase* ending, so their responses about the monomers of DNA polymerase had to be considered in the light of their interpretation of the molecule's name. Even students who could confidently state that "enzymes are proteins" found this particular enzyme hard to categorize.

Enzyme function may also involve alternate understandings. Students learned that the enzyme helicase "unzips" the DNA double helix, while DNA polymerase "pastes" in new bases. From this strong association between the enzymes and the DNA strand, some students formed the belief that enzymes were nucleic acids. In a similar fashion, a few students believed that where the enzyme amylase was present, they should get a positive test for starch or sugars, indicating a mental connection between the enzyme and its substrate or product that led to a belief that the enzyme was the same material as the substrate, or contained the product. A strong belief that all enzymes are proteins appeared necessary to overcome this associative alternative conception.

These findings suggest that an established mode of thinking at the micro level is necessary when forming new scientific concepts around molecules and their functions. Thinking at the micro level was difficult for all students. While students who began the term with high-PNM scores more often spontaneously used micro-level thinking, those with low-PNM knowledge were not entirely without some concept of the nature of biomolecules. Their concepts were often alternative concepts, grounded in their beliefs about human nutrition, and had a logical structure of their own that will be discussed in a later section.

Relationship between student PNM knowledge and their final understanding of biological molecules

The initial survey questions were repeated on the final exam. These and data from the interviews were analyzed to assess student understanding of biological molecules at the end of the term. Though no new concepts were uncovered, most students demonstrated at least some changes in their understanding of molecules as a result of instruction. Data from the questions embedded in the final exam were scored and the scores compared with the initial PNM survey scores. While all students showed at least some improvement, there was a significant correlation between initial PNM knowledge and final knowledge of biological molecules ($r = 0.887$, $p = 0.011$, using a Spearman Rank Order Correlation test).

While PNM knowledge was predictive of the final biomolecular knowledge for the group as a whole, it was not always predictive for individuals. For example, Lorenzo (low PNM) was excited at his final interview by the number of new concepts that he could recall and in the changes that he experienced in his understanding of the biomolecules. Though he began to link lipids with carbohydrates in the final interview, he recognized this as he spoke and corrected himself:

> Oh, that brings a lot of things to mind, also of course carbohydrate is an organic molecule, ring-shaped molecule, composed of carbon, carboxyl group, oxygen, all of those things. It brings to me, um, also fuel, you know, fuel for the body, fuel for the plants, structure for the plants, the cell, fuel for our body too, the sugar, the glucose, the fructose, the lactose that the body needs. I look at the, I look at carbohydrates for example would be like the um – esters? I'm not – not esters, what am I saying? Like cholesterol and those molecules – am I in the wrong part? Wait. Carbs.

Another student, Julie, was a low PNM student who retained her alternative conceptions at the end of the term. While she could recall activities that she had engaged in during the course, she did not fit new knowledge into her existing framework. When asked to name specific molecules, she could not recall any specific carbohydrates and only one protein, which she recalled in the context of her prior nutritional knowledge:

> Well, I don't know, they're [proteins] good for like, you need them to build like keratin and stuff like that, so I know that they're like, you need them to grow, like for your body to make certain things. And I know that they're made up of amino acids. Um, so when you need to like produce certain things, like keratin and stuff like that, um, I guess like some of those [protein bars] are good 'cause if people don't' eat enough like meat or something then they have to make up for it to get enough protein.

Clearly a low PNM score, while important, was not a predetermining factor in this course. The difference between Lorenzo and Julie may lie in other factors beyond prior knowledge.

Underlying Assumptions

Throughout the course, students made statements about the biomolecules that reflected understandings at variance with the target concepts. These statements were grouped into categories that appeared to reflect underlying assumptions about the nature of matter. The categories are summarized in Table 4.

Table 4. Student assumptions underlying alternative student reasoning about the biological molecules.

Student alternative assumptions	**Example of alternative conceptions expressing these assumptions**
As goes macro, so goes micro	Fat molecules are round and bouncy. Protein molecules are strong.
Source = substance	Examples of fats are potato chips, bacon, and butter. Starch contains sugar, so it should test positive for sugar.
Molecule/energy equivalence	Sugar is energy. Calories are a kind of fat. Plants get food from the sun.
Like acts upon like	DNA polymerase acts on DNA, so it is a nucleic acid. Amylase acts on starch, so it is a carbohydrate.

Functional equivalence	Sugars are fats (or contain fats) because they both contribute to weight gain. Protein is a kind of carbohydrate because it gives energy.
Functional limitation	Protein is needed only for energy and muscle building. Fat is needed only for energy.

As goes macro, so goes micro: While this was not frequently expressed, students sometimes associated the structure of molecules with the nature of the macroscopic substances. This assumption was most strongly expressed in Tasha’s (high-PNM) sketch of a fat molecule as large and round, and her description of the molecules as “bouncy.” Seth (low-PNM) believed that fat molecules were “flabby” while protein molecules were “strong.” This associative equivalence may also help explain why students often believed that carbohydrate-rich foods should also contain fat: these foods are often served with fat-rich accompaniments, such as butter. The dissociation between carbon dioxide and the carbon-based products of photosynthesis is related to this assumption. To students, carbon dioxide is a gas, wood and other plant tissues are solid, and it is difficult for the students in this study and in other studies (i.e. Schneps & Sadler, 1989; Hazel & Prosser, 1994) to make a mental link between the two.

Similar assumptions have been noted in the PNM research literature. Nieswandt (2001) found that students would assume a loss of identity if a substance essentially changed form in a reaction by becoming part of a gas. Talanquer (2006), in reviewing PNM literature, described an assumption of *Continuity* used by students describing matter: when matter is divided into small particles, the particles should resemble the macro-level substances in appearance and physical qualities.

Source = substance: When asked to give examples of proteins, carbohydrates, and lipids, the majority of student responses at the start of the term listed foods that contained these substances. Distinguishing between the source of a molecule, such as a food, and the molecule itself, such as a protein, was conceptually difficult. One source of this equivalence came out in conversations with three students who said that in nutrition courses, meat had been referred to as “a protein” and bread called “a starch.” Analysis of foods to demonstrate that they contained many different molecules helped students move to a more precise use of the terms “starch” and “protein.”

Beyond the semantics of health and nutrition courses, students also made mental equivalences between the large biomolecules and their monomers. Students predicted that since starch is made of simple sugars, that starch must *be* a kind of sugar. Presenting students with contrary evidence – demonstrating a Benedict’s test on starch solution – confronted the initial assumption of a positive test but was not always sufficient to help them form another, more scientific explanation. Talanquer (2006) noted a similar assumption among students describing matter. The assumption of Essentialism describes matter as having underlying qualities that determine the identity of the material. Nieswandt (2001) also noted an assumption of essentialism in chemistry students who believed that a material’s identity was conserved if they could follow it through a given set of reactions – that iron remains iron with all the properties of iron even when part of iron oxide.

Molecule/energy equivalence: Initial surveys and interviews contained definitive statements asserting that sugar *was* energy. These students spoke of energy in terms of a substance, an ingredient in food, and a nutrient itself. The belief that energy is a material is well-documented elsewhere in the literature (e.g. Watts, 1983), so it was not surprising to find this belief among this set of students. The material assumption helps explain the belief on the part of some students that calories are a kind of fat: these students assumed that calories are a material substance or a food ingredient, and believed that foods that contain a lot of this perceived substance can contribute to weight gain. The material assumption also contributed to student beliefs that plants get either "food" or materials that they need to make food from the sun. Even when reminded that the sun is millions of miles away, too far for it to be a substantial source of materials, there was persistence on the part of some students to believe that plants received materials from the sun. Perception of light energy as a material explains this belief. Again, Talanquer (2006) described the assumption of *Substantialism* among learners who believed that processes or abstract concepts have the properties of material substances.

Like acts upon like: In studying protein synthesis, students came to believe that the enzymes acting upon DNA were themselves nucleic acids. Some believed that if DNA codes for proteins, it must *be* a protein. On occasion, students stated that the source of amino acids for building proteins was the DNA itself, conflating "codes for amino acid sequence" with "contains amino acids." Students make similar assumptions regarding enzyme activity on other polymers: some believed that the enzyme amylase, which acted upon starch, must itself be a carbohydrate, reporting that if amylase were tested with the reagents used in lab, it would test positive with Lugol's solution (the test for starch). It is possible that the matter-based "black box" ontology described by Barak, et al., (1999) contributed to this assumption. Students recognized that proteins came out of the process of protein synthesis, and that amylase mixed with starch produced sugars, but without moving to a process-based ontology, focused on inputs and outputs rather than seeking to understand the process.

Functional equivalence: Students frequently expressed the belief that carbohydrates contained fats or that sugars *were* fats. While in part this might be traced to imprecise use of the terms in dietary product literature or nutrition literature, the equivalence stated by this group of students was that both carbohydrates and fats were sources of energy, or were forms energy (molecule/energy equivalence), and consequently must be the same or similar substances.

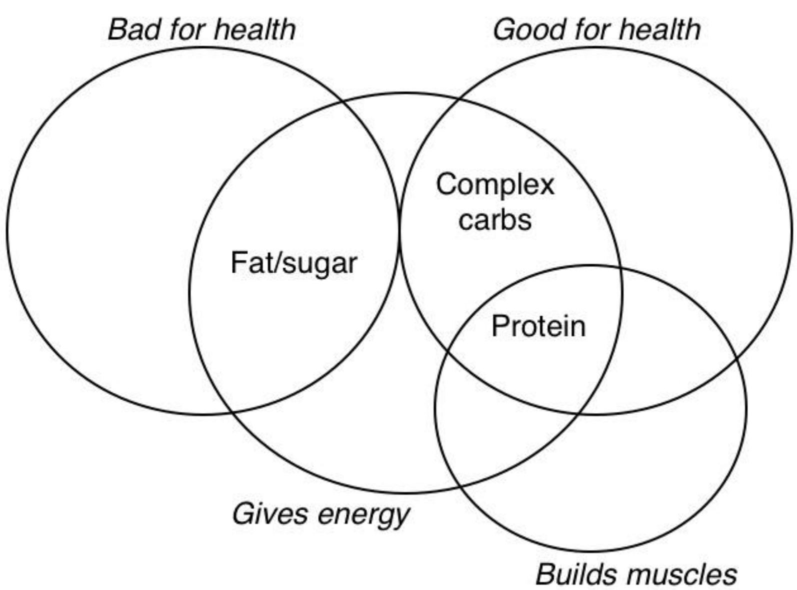
Functional limitation: In describing the roles of biomolecules in living organisms, most students reduced the roles to one or two functions, usually related to human nutrition. Carbohydrates were for energy. Protein was for energy and muscle strength. Fat was for energy and, occasionally, insulation. The tendency to conceptually limit each substance to one or two functions made understanding the wide and varied roles of proteins difficult. Functional limitation may help explain why some students conceptually disconnected the concept of "enzyme," specific molecules with wide range of functions, from the concept of "protein," a nutritional substance with a narrow set of functions. Talanquer (2006) describes *Fixation* heuristics that can limit students' thinking about molecular systems. *Functional limitation* may be a subset of a *Fixation* heuristic that constrains student understanding of molecular roles in living systems.

This set of common underlying assumptions appeared to affect student thinking throughout the term, and influenced the ways in which students categorized the biomolecules as they reasoned about these molecules during class activities.

Logical structures in student alternative categories

Figure 1 expresses the students' alternative ways of classifying proteins, carbohydrates, and lipids as overlapping functional categories. Fats and sugars are combined in this figure, as the merging of these two substances was a frequent alternative conception. Both of the substances were linked in student statements with the concept of energy, though some students believed that fat was an energy source of last resort. Tasha, for example, described fats as "hard to process" in her initial interview, believing that the body preferred to store fats rather than expend the effort required to "process" fats into energy. Complex carbohydrates, in addition to supplying energy, were often spoken of in terms of healthful properties, and hence the inclusion in "good for health." Protein was believed by most students to be primarily a source of energy for the human body, and far less associated with tissue-building and enzyme function except for muscle building, even in the final interviews. Students operating in this framework of alternative categories tended to have difficulty recalling and understanding individual proteins, such as specific enzymes or transport proteins.

Figure 1: Student alternative conceptions about the biomolecules expressed as overlapping functional categories. Note that fats and sugars are often grouped in the same category since students often believe they are similar: that fats contain sugar, or that sugar contains fat.



Alternative categories may explain why some students encountered difficulty when reasoning about the biomolecules. Where "protein" and "fat" were perceived as nutritional substances with little or no variation, and categorized by nutritional function, students often experienced a disconnect between their concept of *protein* as a continuous substance and *proteins* as discreet molecules with many and varied functions; hence the separation of the concept of *protein* from the concept of *enzyme* experienced by some students. While these students could repeat the information that "enzymes are proteins," they had difficulty remembering that enzymes are made up of amino acids. Furthermore, students tended to ascribe highly limited functions to each of the substances. If fat is viewed as simply a source of energy and nothing else, little cognitive room is left for understanding other roles. Again, this may contribute to a conceptual disconnect between *fat* as a nutritional substance and specific *fats*, such as phospholipids.

Heathful or unhealthful properties were also employed as students categorized these molecules. Fats, sugars, and occasionally starches were conceptually linked as agents that cause poor health. Fats were almost universally perceived as "bad for you," particularly in the initial interviews, associated frequently with greasy foods, junk foods, and processed foods. Refined sugars were also "bad for you," though sugars found naturally in fruits were perceived in a positive light. Starch, if spoken of in the context of junk food or processed foods, was sometimes placed in the "bad for you" category. Interestingly, a few students classified sodium as a fat because they associated it with unhealthful foods, placing sodium squarely in the "bad for you" category of substances.

In contrast, proteins and complex carbohydrates derived from whole grains were believed to be agents of good health. Proteins were universally viewed in a positive light as a source of energy and strength for muscles. Carbohydrates were viewed as "good for you" if they were complex, though "complex" could mean "from whole grains" rather than a polysaccharide.

Overall, student alternative categorizations of biomolecules were strongly linked to nutritional roles, which seemed to create functional equivalences. Nutritional roles eclipsed the many roles of specific biomolecules that students learned over the course of the term, severely limiting perception of functions. Moving to a scientific way of categorizing these molecules required that students make a cognitive leap between a generalized and non-molecular view of each substance (i.e. *protein*, singular) to a view that each familiar substance name was actually a category that contained many specific, discreet, and functional variations on a molecular theme (i.e. *proteins*, plural).

Summary of Results and Discussion

This section was organized around student understanding of PNM, student understanding of biomolecules, and the relationships between these sets of knowledge in order to find answers to the original guiding questions.

Does a relationship exist between students' understanding of the particulate nature of matter and their understanding of proteins, carbohydrates, and lipids at the start and at the end of the course? At the start of the course, differences in PNM knowledge were found between students, such that students could be divided into high-PNM and low-PNM groups. However, the knowledge of all students regarding the biomolecules was so low that no correlation was found between PNM knowledge and biomolecular knowledge. By the end of the term, differences emerged. Those with higher PNM knowledge tended to show more scientific understanding of biomolecules than those with low PNM knowledge.

Does a relationship exist between a student's understanding of the particulate nature of matter and that student's emerging knowledge of biological molecules within the context of three biological processes: enzyme activity, photosynthesis, and protein synthesis? Over the course of the term, students in general learned that large biomolecules are composed of smaller molecules, that some molecules (such as enzymes) play specific roles biological processes, and that molecules themselves are made up of atoms, suggesting an increasing development of PNM knowledge. However, one persistent barrier to understanding was a macro-level nutritional understanding, particularly around proteins. Some students demonstrated a resistant mental separation between *protein* as a nutritional substance and *proteins* as individual molecules with specific functions. This separation between a nutritional mode of thinking – essentially continuous substance view – and a molecular mode of thinking appeared correlated with prior PNM knowledge. Those students with high PNM at the start of the course were those who were better able to grasp the molecular nature behind the familiar nutritional terms. This knowledge was necessary in understanding biological processes.

Do logical structures exist in undergraduate student conceptions when reasoning about the biological molecules? This study found logical structures in alternative conceptions around the biomolecules. First, student ideas appeared to arise from underlying assumptions about the nature of matter, several of which map onto prior PNM research. Intuitive ideas about matching qualities – "as goes macro, so goes micro," "source = substance," "energy = matter" – provide a lens through which students view both old and new information about the biomolecules. They suggest that students obtain their clues about the micro world from macro-level properties, which is perfectly reasonable, as these are usually the only sources of data that they have to work with. Students rarely have access to the types of equipment and the specialized knowledge that has been used to develop scientific models about the nature of matter.

Second, student alternative categories of the biological molecules could be described as overlapping categories based on the most available information: superficial nutritional information available through the media and food packages. Alternative categories centered around perceived utility ("protein is a source of energy") and perceived value ("fats are bad for you"). Substances that had similar qualities were categorized together; hence an equivalence between sugar and fat as both were perceived as having the same utility ("source of energy") and the same value ("bad for you").

This study found relationships between PNM knowledge and the ability to learn about biomolecules, as well as describing the structure of alternative conceptions. The next section will discuss implications of these findings.

Conclusions

Studies on student understanding of the particulate nature of matter generally show a learning sequence in which elementary students hold many alternative concepts, middle school students hold few alternative concepts, and high school students hold fewer still (Novick & Nussbaum. 1981; Hazel & Prosser, 1994; Talanquer, 2006; Löfgren & Helldén, 2009). Often implied is the notion that by college, most students will have discarded alternative concepts regarding matter in favor of scientific understanding as a result of instruction in science classes.

Clearly, for the students in this study, that was not universally the case. Nearly half of the students came to class with either alternative views of matter or no views that they were able to express. This put them in at a cognitive disadvantage in a traditional lecture-and-lab course when learning about the biomolecules and molecular-level processes in living systems. What can be learned from this small group of students and from prior studies that can help remedy the situation? From this study, two lessons stand out:

Age is not predictive of molecular knowledge

First, we conclude that all college students in this study and in other studies have at least heard of proteins and other biomolecules. They recognize the names and have a few ideas about the nutritional value of these classes of molecules. This was not surprising given that all of the students had encountered the terms in the media and on food packaging. What they appear to lack is a molecular-level understanding of the biomolecules. This may be due to lack of repeated exposure to knowledge of these substances at the molecular level, or long-term retention of such knowledge, or both.

None of the students in this study were science majors, but most of the students had taken science courses at some time in their past. Some were older students who had not had a science course in many years, and were worried about how little they remembered. Some were younger students who had taken other science courses recently to fulfill their core curriculum requirements or who recalled high school science courses taken within the few years prior to the study. Why did all of the students arrive with so little knowledge of the biomolecules beyond a very limited set of nutritional ideas?

It would be overly-simplistic to ascribe their lack of scientific understanding entirely to the quality of prior instruction. The students came from different backgrounds, each receiving science instruction from different teachers at different schools and on differing timelines. The amount of exposure and the opportunities to learn may have some relation, in that beyond textbook figures, students could not recall seeing diagrams of protein molecules or other biomolecules. In their everyday lives, students simply did not encounter these models and concepts. It is probable that any prior learning about molecules was diminished over time due to the lack of opportunity to practice thinking about such abstract representations.

Another, more robust answer may lie in the logical structure of alternative conceptions that students applied when thinking about biomolecules. Consistency within alternative conceptions can render them resistant to conceptual change (Pozo & Gomez-Crespo, 2005). Resistance to change can also arise from the fruitfulness, or daily functionality, of alternative conceptions (Posner, et al, 1982). The fruitfulness of alternative conceptions and the lack of opportunity to use and practice scientific understanding may help explain why any prior knowledge of biomolecules derived from other science courses was difficult to recall.

For these students, their alternative conceptions “worked.” A highly limited, nutritional understanding of carbohydrates, fats, and proteins provided a useful rubric for deciding what foods to choose for good health and what foods to avoid. Rarely does daily life require these students to understand the intricacies of photosynthesis beyond knowing a few elementary ideas: plants take in carbon dioxide, give off oxygen, and can be use for food. Rarely are these students required to distinguish between thousands of proteins in organisms, when a nutrition label says only "protein."

Students tended throughout the term to view the biomolecules first as nutrients, and only with effort as unique molecules with specific functions. The nutritional view is familiar and functional; the scientific view is unfamiliar and sometimes at odds with students' nutritional framework. While the scientific view answers many questions, they may not be the questions that students are intrigued by, or have even thought of.

PNM knowledge is somewhat predictive of ability to learn biomolecular knowledge

Second, we conclude that prior PNM knowledge is an important factor, but it is not a predeterming factor. All students found that the molecular-level content of the course was difficult. Those with high PNM knowledge tended to form scientific understandings more readily than those with low PNM knowledge, even though there was no strong correlation between PNM knowledge and molecular knowledge at the start of the term.

What seemed to give high-PNM students an advantage during the learning process was a better ability to reason their way toward a scientific understanding. Whether this was due to higher level of knowledge about matter or due to a higher level of reasoning was not discernable within the assessments that were applied. In some instances, however, knowledge appeared to be important in forming new understanding. Knowing that proteins were polymers composed of amino acids and knowing that enzymes were proteins were both important in knowing that enzymes were made of amino acids. All three pieces of knowledge were needed for students to understand that genes, which code for proteins, also code for enzymes since enzymes are proteins. Students who held the concept of *protein* as a singular nutritional substance, separate from *proteins* as many and highly varied structures composed of amino acids, appeared to struggle the most with linking their knowledge of enzyme activity and protein synthesis. This emerged anecdotally in lab conversations, so could not be quantified, but seems to be a promising line of further research.

However, this study and other studies (Bledsoe, 2007; Bledsoe & Flick, 2012) show that students are not doomed by lack of prior knowledge. The differences between Lorenzo and Julie, two low-PNM students described earlier in this paper, suggest other affective factors that were not measured in this study may play a significant role. In Lorenzo's case, a positive orientation toward science suggested personal motivation may have contributed to his ability to acquire a scientific understanding. The enthusiasm that Lorenzo displayed in his final interview, where he could hardly get his ideas out fast enough, was characteristic of him throughout the term. Julie, on the other hand, did not display a strongly positive orientation toward science. She was not outwardly negative, either; she simply did not display Lorenzo's eagerness to learn. Similarly, Bledsoe (2007) found that prior content knowledge was not predictive of success in a problem-based engineering laboratory course. Other factors, such as study habits and orientation toward the subject appeared to play a role in problem-solving success.

Molecular knowledge and biology instruction

A scientific understanding of biomolecules is valuable and informative for all students when making decisions related to health, the environment, and other topics of interest to them. Thus helping students develop a scientific understanding is worth the considerable effort that it may require. How can educators help students form an understanding of biomolecules on the molecular level?

While PNM knowledge is not a predetermining factor, it does appear to play an important role in how students view biomolecules. This study shows that educators cannot make assumptions about the level of PNM knowledge in their students based solely on age. Providing multiple opportunities to learn and practice PNM knowledge may be important in helping students understand molecules and molecular processes at all levels of instruction.

Studies in chemistry education have shown the efficacy of using instructional models, both physical models and computer-based models, for increasing student understanding of matter. When students manipulate models, make predictions, and observe the results of manipulated changes, they are better able to understand chemical processes by understanding the processes at the molecular level. Canning and Cox (2001), for example, noted that instruction about biomolecules is often limited to illustrations in textbooks. Using computer models allowed students to understand the dimensional nature of proteins, which was necessary for students to grasp how proteins fold into biologically functional structures. Herman et al. (2006) noted an increased conceptual understanding of molecules among high school and college chemistry students who used physical models of molecules. However, Kelley and Jones (2008) found that animations used in chemistry instruction can create simplistic or incomplete understanding of the nature of matter. While use of animations increased student recall of information, it was important that the teacher make frequent and explicit connections between scientific vocabulary and chemical processes. Harrison and Treagust (1996) found that social learning was important. Students who engaged in group discussions, comparing attributes of various models and analogies, tended to use the models more consistently and formed more scientific concepts than those who did not engage in social learning. Further research will be needed to determine whether models will increase molecular understanding among students and whether these methods will increase the longevity of scientific understanding.

It is also important to acknowledge and make use of student prior conceptions (Hammer & van Zee, 2006). When attempting to assimilate scientific understanding, if students are left to their own devices, they may grow frustrated in attempting to force scientific knowledge into their prior alternative framework. The knowledge may be memorized long enough to supply answers for exams, then discarded as irrelevant. By understanding student alternative frameworks, educators can better develop instruction that begins where students are, helps them confront their prior knowledge, allows them to discover which parts of it are useful in a scientific framework, and helps them construct evidence-based explanations for everyday phenomena. This study provides insight into student alternative conceptions around biomolecules that may inform future studies and future instruction.

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